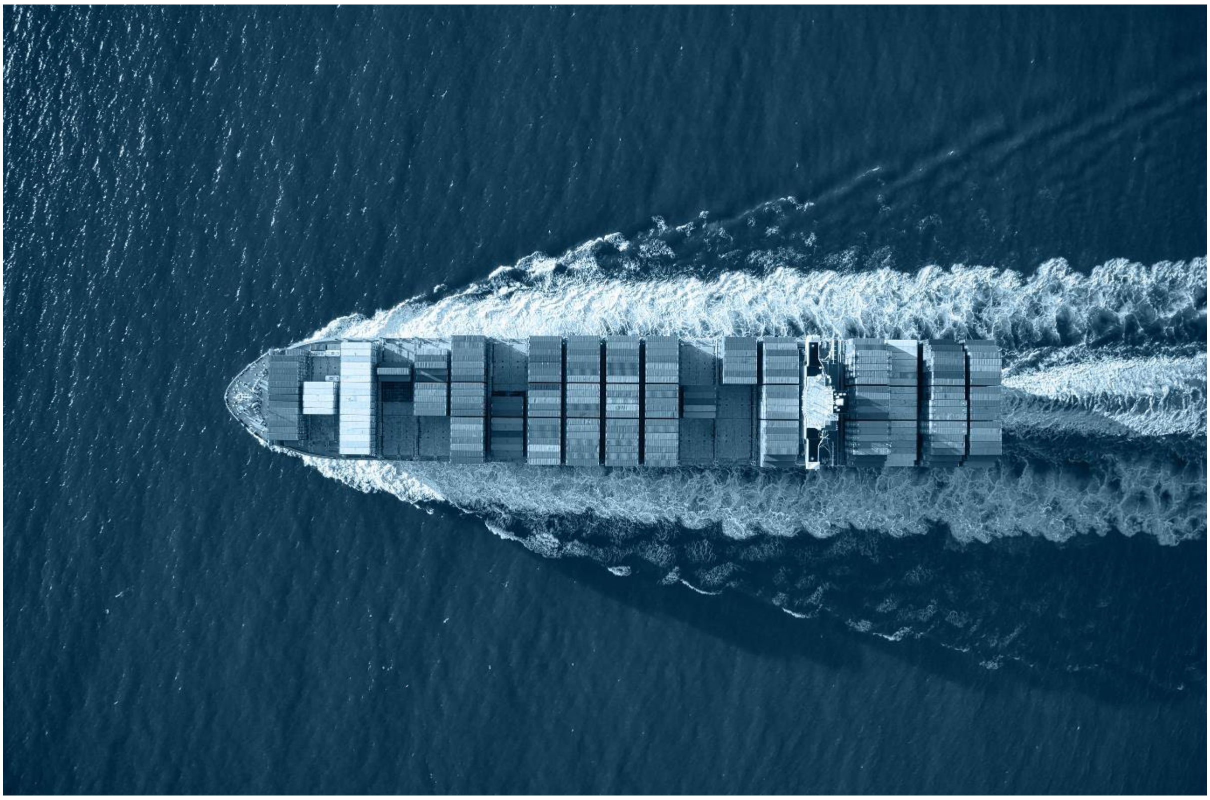
ADMO Deliverable 1.2. - Roadmap to Digital Maritime Operations: Regulatory and Practical Perspectives



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Introduction

Digitalization of maritime operations leverages advanced technologies to transform business models and create new value-producing opportunities. This process incorporates sensors, connectivity, data analytics, artificial intelligence, and automation to enhance operational efficiency, improve safety, reduce environmental impact, and enable innovative business models.

Maritime operations face unique connectivity challenges requiring specialized research attention. The industry operates in harsh, remote environments with extreme weather conditions and vast distances from shore infrastructure - creating distinct technical demands unlike those in land-based industries. Solving these maritime-specific challenges is crucial for achieving the full potential of digital transformation in the sector.

Current maritime connectivity systems (described in ADMO deliverable 2.1.) provide basic operational communications, but next-generation mobile networks can significantly enhance these existing capabilities by enabling higher bandwidth, lower latency connections necessary for real-time data exchange, remote operations, and advanced automation. The integration of 4G/5G technologies with traditional maritime systems creates a complementary communication ecosystem that maintains safety while enabling digital innovation.

The ADMO project builds directly on findings from previous maritime digitalization initiatives, particularly the Sea4Value program[1] regarding digital ecosystem development in marine environments. By addressing connectivity gaps identified in these earlier works, ADMO studies the critical next steps in the evolution of maritime digital transformation.

Solving these connectivity challenges effectively will unlock the enablers necessary for comprehensive maritime digitalization. Rather than insurmountable obstacles, these challenges represent strategic opportunities - when properly addressed through appropriate technical solutions and ecosystem development, they become the foundation upon which the next generation of efficient, sustainable, and innovative maritime operations can be built.

The ADMO project addresses these challenges by evaluating mobile network performance in maritime settings, particularly focusing on 4G and 5G capabilities in archipelagic regions. Through comprehensive measurement campaigns and stakeholder workshops, the project identifies both the potential and limitations of current connectivity solutions while establishing performance requirements for key maritime digitalization use cases.

Use Cases

The ADMO project focuses on several key use cases for digitalization in maritime operations:

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[1] DIMECC: Sea4Value – Future Fairway Navigation – Final Report:https://www.dimecc.com/wp-content/uploads/2023/04/Sea4Value_final-report-low.pdf

1. **Remote Monitoring**: This involves the use of sensors and communication networks to monitor ship systems and environmental conditions remotely. It can help in proactive maintenance and decision-making.
2. **Remote Operations**: This extends beyond monitoring to include other ship operations that can be controlled remotely, for example navigating the ship.
3. **Automated Vessel Operation**: This involves the use of advanced automation and artificial intelligence technologies to enable ships to operate with minimal human intervention. There are several levels of automation, ranging from automation of some functionalities to assist the human to fully autonomous operation of the vessel.
4. **Remote Pilotage**: This refers to the remote assistance and/or control of a ship's navigation, often from a shore-based center. It can enhance safety and efficiency, especially in complex or hazardous navigational situations.
5. **Smart Fairway Services**: This includes the use of digital technologies to enhance navigation safety and efficiency in fairways, such as real-time traffic information, dynamic routing, and automated reporting.

Remote Monitoring involves the use of various technologies to collect data from the ship and transmit it to a remote location for analysis. It requires reliable and low-latency data communication between the ship and the monitoring center. The data collected can include information about the ship's position, speed, course, and other relevant factors. This use case is crucial for maintaining the health of machinery, using predictive diagnostics, and communicating critical information inside and outside the ship.

Remote Operations refers to the ability to control certain aspects of the ship's operations from a remote location. Like remote monitoring, it requires reliable and low-latency data communication between the ship and the operations center. However, in addition to simply collecting and analyzing data, remote operations involve making decisions and sending control commands back to the ship.

Automated Vessel Operation involves the use of autonomous systems on the ship itself to carry out operations without the need for human intervention. These systems rely on the same environmental detection techniques as remote monitoring and operations, but they also need data transmission and remote updatability for sensors. Autonomous ships are able to avoid collisions by sensing the environment and making independent decisions.

The similarities among these three use cases include the need for reliable and low-latency data communication, the use of data from the ship for decision-making, and the goal of improving the safety and efficiency of maritime operations. The differences lie in the level of control and decision-making involved. Remote monitoring is primarily about data collection and analysis, remote operations involve control from a distance, and automated vessel operation involves decision-making on the ship itself.

Remote pilotage is a concept that allows pilots to guide ships remotely. This cloud-based service creates a "safe tube", a dynamic route for the ship considering various factors. Remote pilotage doesn't cover port maneuvering or apply to inland waterways. While not yet practiced globally, AI and machine learning may facilitate its future implementation. Remote pilotage will not be ready to be trialed during ADMO project timeline, but we will aid in the development of the systems through connectivity and quality of service measurements.

Smart Fairway services aim to enhance services for autonomous maritime traffic and other emerging uses of territorial sea. These services involve the creation of a dynamic route for the ship that takes into account the waterway characteristics, the weather conditions, and the other traffic. The dynamic route is created using data from the ship and other sources. The MaDaMe project, which stands for Maritime Data Methods for Safe Shipping, will study and pilot these Smart Fairway services. It is coordinated by Turku University of Applied Sciences. The project aims to support national authorities responsible for maritime traffic management in developing common, cyber-secure, digital transport infrastructure services in the Baltic Sea Region. For connectivity, the MaDaMe project will utilize VDES (VHF Data Exchange System), an extension to AIS (Automatic Identification System), adding two-way data channels over VHF. This system allows for more secure and efficient data exchange, which is crucial for the successful implementation of Smart Fairway services. ADMO will support MaDaMe by studying how mobile networks could be used to transmit smart fairway services.

ADMO workshop on 5G use cases for maritime connectivity

The outcomes of the workshop held on 24.04.2024 revealed several important insights across the key maritime digitalization areas.

During discussions on **Remote Monitoring**, participants emphasized the necessity of monitoring ship systems and cargo remotely. The workshop highlighted how this information would be valuable for predictive maintenance and assessing vessel status. From a technical perspective, the data requirements were determined to be modest, at the kilobit level, without strict latency constraints. An important question was raised regarding the need for global coverage for these monitoring systems. This aligns closely with ADMO's Remote Monitoring use case, which similarly focuses on using sensors to collect data for proactive maintenance and decision-making, though the workshop added specific technical parameters around data requirements.

For **Remote Operations**, the workshop delved into practical control inputs such as helm and throttle systems. Participants noted the need for high bitrates to support camera streams and real-time video transmission, which would be essential for remote operational control. The frequency of data transmission was also extensively discussed, as consistent and timely data flow would be critical for safe remote operation. These outcomes directly support ADMO's Remote Operations use case, which emphasizes the need for reliable, low-latency communication to enable remote control of ship functions. The workshop added valuable technical specifications regarding the bandwidth requirements for video feeds that would be necessary for effective remote control.

The **Automated Vessel Operations** discussion covered a wide range of data needs, including dynamic fairway data for navigation, autopilot control systems, vessel status monitoring, access control protocols, remote piloting capabilities, navigation data processing, radar data interpretation, voice communication, and weather information integration. Participants stressed the high requirement for maintaining stable connections from the beginning of a journey to where piloting operations are conducted. Key Performance Indicators for connection quality were discussed, with participants agreeing that less than 1-second delay would be essential for safe automated operations. These outcomes closely complement ADMO's Automated Vessel Operation use case, adding specific data types and connection quality metrics that would be needed to achieve the autonomous capabilities described in the project.

The workshop also explored **Wireless on-ship sensors**, noting that while there are potentially massive numbers of sensors onboard modern vessels, the data rate per individual sensor is typically not substantial. However, participants identified emerging real-time requirements for certain critical sensors. The discussion touched on the need for small, cost-effective radio units, indoor mapping technologies, and the potential for opportunistic mesh networks to improve on-ship connectivity. This area extends ADMO's Remote Monitoring use case by detailing the on-ship infrastructure needed to collect the data that would later be transmitted to shore-based monitoring centers.

Finally, regarding **On-Ship Infotainment**, the workshop addressed local media delivery systems and ship internal information distribution networks. Participants recognized that high capacity would be required due to the potentially large number of users accessing these systems simultaneously. While this area isn't directly mentioned in the main ADMO use cases, it represents an important practical consideration for vessel digitalization that would affect crew welfare and passenger experience on automated or remotely operated vessels.

Overall, the workshop outcomes provide practical, technical depth to the conceptual framework outlined in the ADMO use cases, offering specific parameters, requirements, and challenges that would need to be addressed to successfully implement each use case in real-world maritime operations.

Key Performance Indicators (KPIs) for the Use Cases

The performance of the communication network service in supporting these use cases can be evaluated using several KPIs:

1. **Bitrate**: The data transfer rate, which should be sufficient to support the data needs of the use cases.
2. **Latency**: The delay in data transmission, which should be minimized to support real-time operations.
3. **Coverage**: The geographical area covered by the communication network, which should ideally encompass all operational areas of the ship.
4. **Scalability**: The ability of the network to handle increasing numbers of users without degradation of service.

Initial KPI definitions were established in ADMO Deliverable 1.1. The table below presents an updated version of these KPIs, incorporating findings from the April 24, 2024 workshop. This revised framework reflects both the original requirements outlined in Deliverable 1.1 and the additional technical insights gained through stakeholder discussions during the workshop.

Use Case	Suggested Key Performance Indicator Values	
Remote Monitoring	• **Bitrate**: Modest requirements (kilobit level) • **Latency**: No strict constraints for basic monitoring • **Coverage**: Global coverage requirements to be evaluated • **Scalability**: Must support multiple ship systems and cargo monitoring	
Remote Pilotage	• **Bitrate**: High bitrate for real-time control, more moderate bitrates are sufficient if only radar and voice communication is needed • **Latency**: End-to-End latency should be less than one second • **Coverage**: Especially in areas where the pilot normally boards and disembarks from the vessel. According to Finnish legislation, remote pilotage is permitted in these defined sections of the fairway. • **Scalability**: Should be able to handle multiple vessels simultaneously, especially in busy ports.	
Remote Operations	• **Bitrate**: High bitrate required to support camera streams and real-time video transmission (magnitude: 10 Mbps) • **Latency**: End-to-End latency should be less than one second • **Coverage**: Continuous coverage required throughout operational areas	

	• **Scalability**: High scalability to support multiple simultaneous operations.	
Automated Vessel Operation	• **Bitrate**: Variable depending on active automated functions • **Latency**: Less than 1-second delay essential for safe automated operations • **Coverage**: Stable connections required from journey start through piloting operations • **Scalability**: Must support a fleet of automated vessels operating concurrently.	
Smart Fairway Services	• **Bitrate**: Relatively low • **Coverage**: Wide coverage for extensive fairway areas •**Latency**: Should be low to ensure timely updates and responses. • **Scalability**: High scalability for multiple users	
Wireless On-ship Sensors	• **Bitrate**: Low per individual sensor, but potentially high in aggregate • **Latency**: Emerging real-time requirements for critical sensors, lower requirements for opportunistic mesh networks • **Coverage**: Need for indoor mapping and opportunistic mesh networks • **Scalability**: Must support a large number of sensors and devices.	
On-Ship Infotainment	• **Bitrate**: High capacity required • **Capacity**: Must support large number of simultaneous users • **Latency**: Should be low to ensure smooth streaming and real-time updates. • **Coverage**: Ship-wide coverage needed for media delivery and information distribution	

Case study: Evaluating 4G and 5G Connectivity in the Archipelago of Finland and Sweden for Autonomous and Remotely Controlled Vessels

Connectivity Heatmap and Network Performance

Turku UAS conducted a comprehensive measurement campaign along the maritime route from Naantali, Finland, through Långnäs, Åland Islands, to Kapellskär, Sweden. This approximately 300-kilometer journey through the archipelago provided a unique opportunity to evaluate mobile network performance for maritime applications.

Our measurement setup, depicted in Figure 1, utilized a Rohde & Schwarz TSME6 RF-scanner with ROMES software running on a laptop, capable of simultaneously monitoring all mobile network signals across multiple operators and frequency bands. The scanner was connected to one of the ship's Promarine proTAC 5311 wideband communication on the upper deck, providing up to 5 dBi gain across frequencies from 800 MHz to 2600 MHz. A GPS antenna was also connected to the scanner to obtain location information.

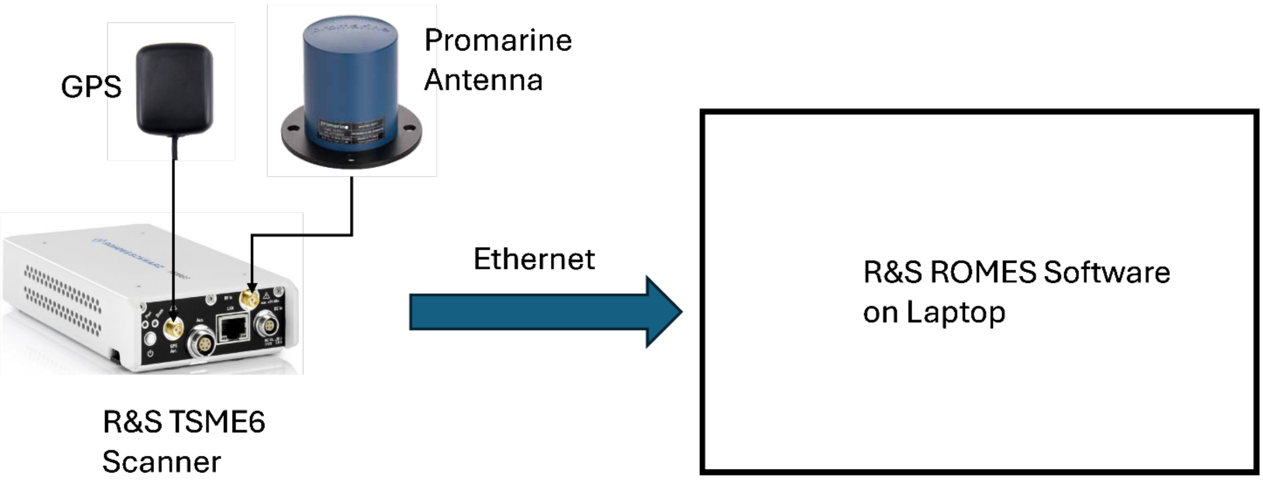

FIGURE 1. MEASUREMENT SYSTEM SETUP SHOWING THE RF-SCANNER CONNECTION TO THE SHIP'S ANTENNA SYSTEM AND THE MEASUREMENT LAPTOP.

Connectivity Coverage Analysis

Figure 2 illustrates the measurement route, showcasing the archipelago regions and open sea sections. The study utilized advanced RF scanning equipment to assess network coverage and signal strength across different frequency bands.

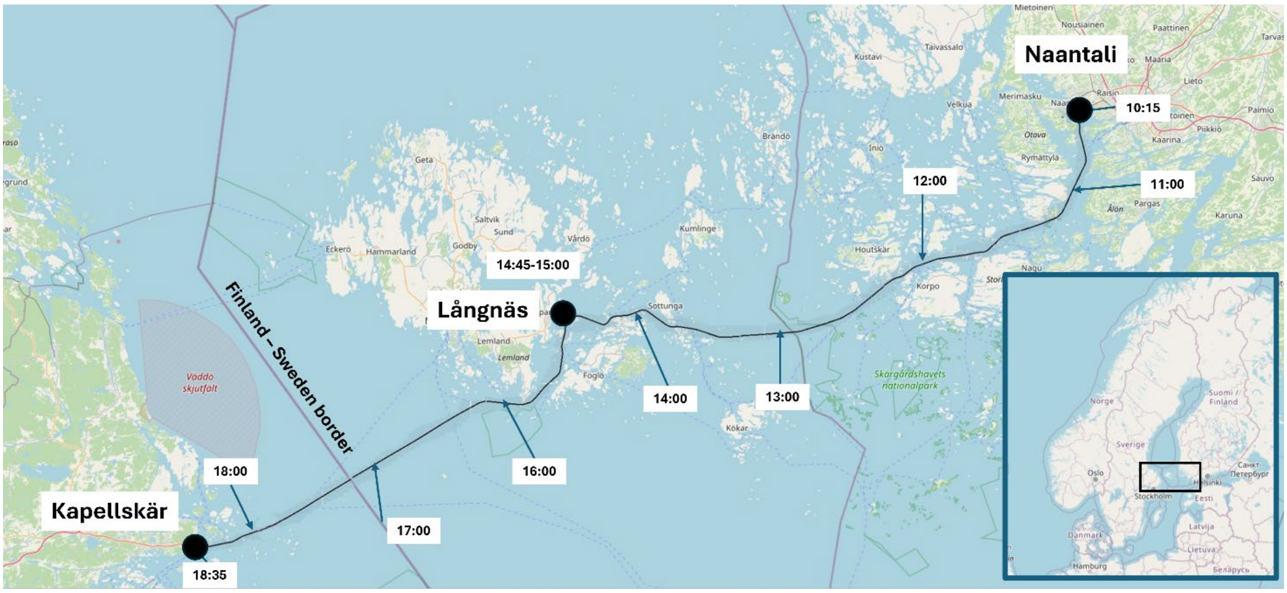

FIGURE 2. MEASUREMENT ROUTE FROM NAANTALI THROUGH LÅNGNÄS TO KAPELLSKÄR, SHOWING THE ARCHIPELAGO REGIONS AND OPEN SEA SECTIONS. MAP SOURCE: WWW.OPENSTREETMAP.ORG

The research presents a comprehensive analysis of Reference Signal Received Power (RSRP) measurements for both 4G and 5G networks across different frequency bands. The measurements were conducted along the Naantali-Långnäs-Kapellskär route, providing insights into mobile network performance in archipelagic maritime environments.

For 5G networks, the measurements covered multiple frequency bands with varying characteristics. Figure 3 illustrates the best RSRP measurements across these different frequency bands throughout the journey. The analysis reveals significant variations in signal strength depending on the frequency band used. Lower frequency bands, particularly those below 1 GHz, demonstrated the most consistent and reliable coverage.

The distribution of these 5G RSRP measurements, visualized in Figure 5, offers a more nuanced view of signal strength variations. This distribution analysis helps understand the probability of receiving different signal strengths across the route, highlighting the reliability and consistency of mobile network coverage in maritime settings.

Similarly, the 4G network measurements, shown in Figure 4, provide a comprehensive coverage analysis across different frequency bands. The results demonstrate the performance of 4G networks in the same maritime environment. Figure 6 complements the primary measurements by presenting the distribution of 4G RSRP values.

The study found that for both 4G and 5G networks, the sub-1 GHz bands (such as 700 and 800 MHz) consistently delivered RSRP values better than -90 dBm across nearly the entire route. The 1.8 GHz band for 4G also performed exceptionally well. In contrast, higher frequency bands (above 2 GHz) showed more limited range, primarily providing enhanced data rates near coastal areas.

This detailed analysis is crucial for understanding mobile network performance in maritime environments. It demonstrates the importance of frequency band selection and provides valuable insights for designing communication systems for autonomous and remotely controlled vessels in archipelagic regions.

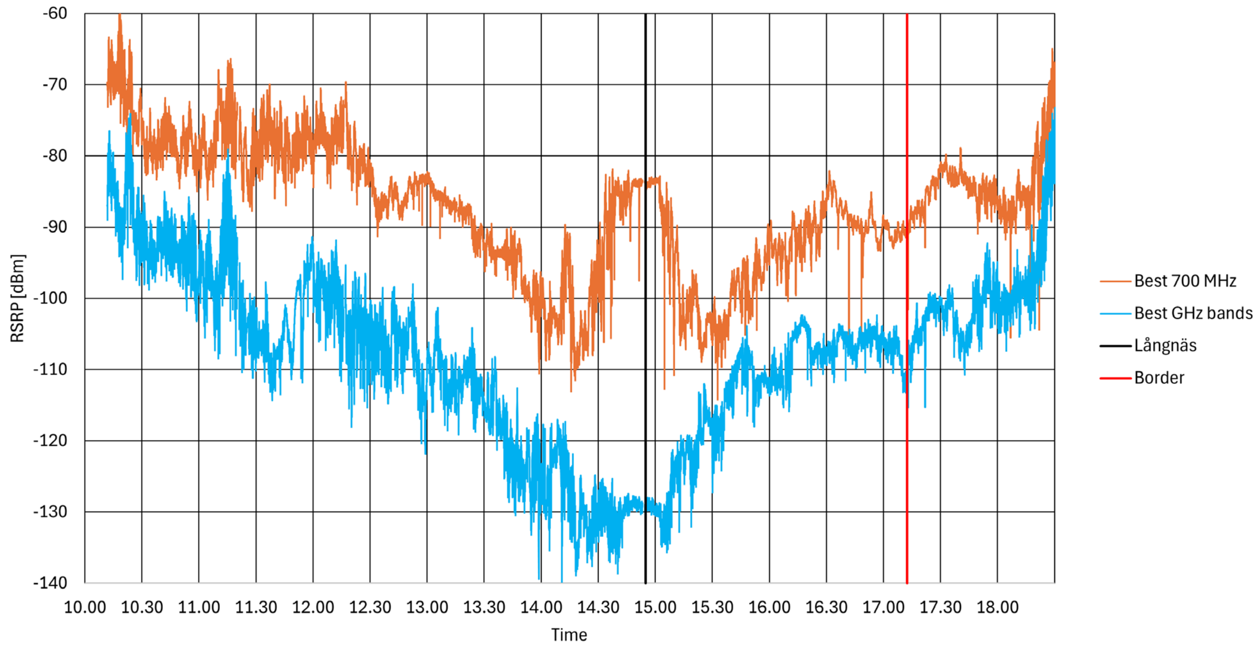

FIGURE 33. BEST 5G RSRP MEASUREMENTS ACROSS DIFFERENT FREQUENCY BANDS FROM NAANTALI TO KAPELLSKÄR.

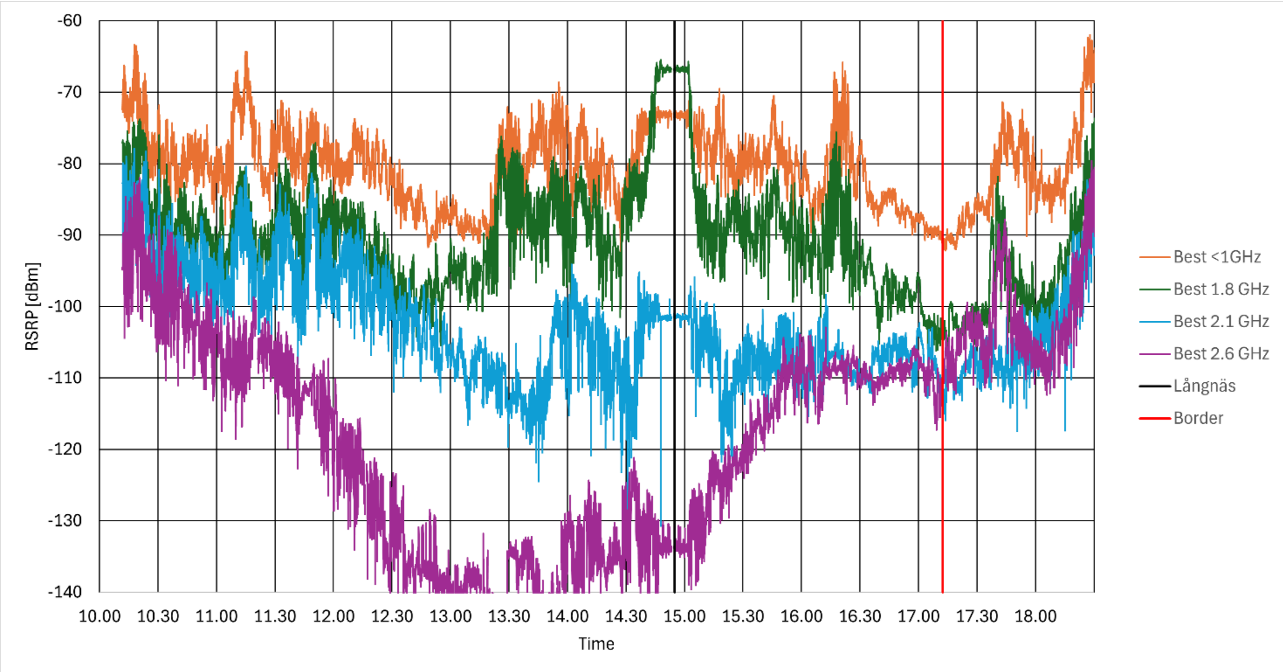

FIGURE 44. BEST 4G RSRP MEASUREMENTS ACROSS DIFFERENT FREQUENCY BANDS FROM NAANTALI TO KAPELLSKÄR

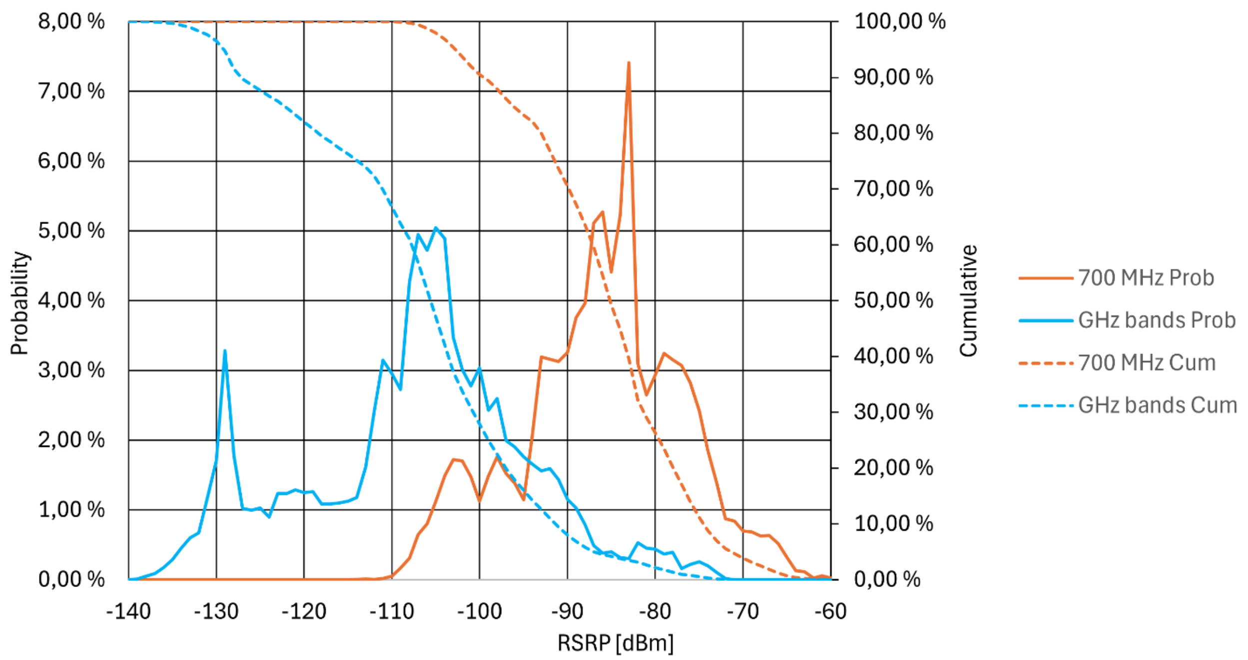

FIGURE 55. DISTRIBUTION OF BEST 5G RSRP MEASUREMENTS ACROSS DIFFERENT FREQUENCY BANDS FROM NAANTALI TO KAPELLSKÄR.

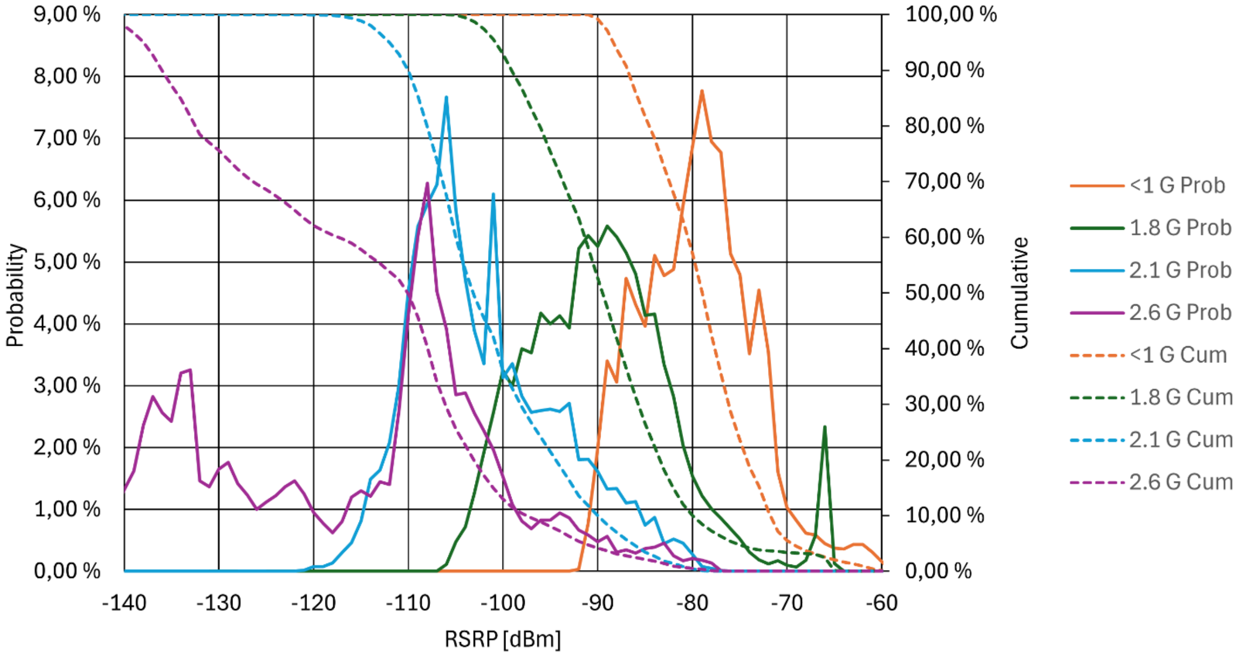

FIGURE 66. DISTRIBUTION OF BEST 4G RSRP MEASUREMENTS ACROSS DIFFERENT FREQUENCY BANDS FROM NAANTALI TO KAPELLSKÄR.

Current 4G and 5G Network Analysis

The measurements revealed several critical insights into mobile network performance in maritime environments. Lower frequency bands, particularly those below 1 GHz, demonstrated the most consistent coverage, providing RSRP values consistently better than -90 dBm. Higher frequency bands above 2 GHz offered enhanced capacity near coastal areas, with the 1.8 GHz 4G band performing exceptionally well throughout the route.

The study's unique approach included positioning the measurement antenna at an elevated height of 25-30 meters above sea level, which likely improved signal reception and provided a more comprehensive view of network coverage.

Coverage Characteristics

The research achieved nearly 100% route coverage (by combining all available operators) through strategic base station placement on islands. However, a minor coverage gap was identified in the open sea area between Åland and the Stockholm archipelago, highlighting the challenges of maintaining consistent mobile network connectivity in maritime environments.

Recommended Network Improvements for Use Cases

For remote monitoring and operations, the study recommends maintaining a focus on lower frequency bands to ensure consistent connectivity. The researchers suggest implementing multi-SIM modems for improved signal selection and developing data preprocessing strategies to manage uplink bandwidth limitations.

Automated vessel operation would benefit from developing intelligent network selection algorithms and integrating satellite communications for hybrid connectivity solutions to allow connectivity to locations where mobile networks are not available. In this measurement campaign, the archipelago has very good mobile network connectivity, but the open sea sections would benefit from satellite connectivity. The study emphasizes the importance of addressing coverage gaps through redundant communication systems to ensure safety-critical functions remain operational.

Smart fairway services can be enhanced by optimizing coverage in areas with limited mobile network infrastructure and complementing existing Automatic Identification System (AIS) and VHF Data Exchange System (VDES) technologies with mobile network data.

Future Network Developments

The upcoming 5G Advanced Release 18 promises exciting developments, including Non-Terrestrial Networks (NTN), advanced sidelink communications, and enhanced hybrid connectivity options. These technologies could significantly improve maritime communication capabilities, especially the NTN would be useful in open sea where no mobile networks are available.

Regulatory and Technical Considerations

Our research, interviews with maritime stakeholders and measurements suggest several potential regulatory and technical improvements to enhance maritime connectivity. These include increasing base station power in sparse coverage areas, exploring lower frequency allocations, and investigating possibilities for new spectrum for mobile networks in low bands (below 1GHz). Potential new spectrum could include releasing some spectrum from Digital TV to mobile networks. converting the 800 MHz band to 5G, and repurposing the 900 MHz 3G band for 5G use.

Additionally, the study recommends optimizing Uplink/Downlink ratios in Time Division Duplex (TDD) networks, because use cases such as remote operations require higher uplink capacities. It should be noted that the selection of TDD frame structure often needs to be coordinated between the networks to avoid harmful interference, thus limiting the possibilities for frame use. Current below 1GHz frequencies for 5G are for FDD, which does not allow UL/DL capacity adaptation. Further, regulations could be developed to support base station mobility in maritime environments to support coverage extension to areas where fixed basestations are not available. Having base stations mobile would be beneficial in situations where temporary capacity is required for specific operations in a certain area, for example when utilizing automated vessels for infrastructure maintenance of offshore wind farms.

Sottunga and Jyddö Base Stations and Network Performance

To complement the comprehensive route measurement, a detailed analysis of local base stations in the Åland archipelago was conducted as part of the ADMO project. The study, documented in ADMO Deliverable 2.3, focused on two specific base stations located in Sottunga and Jyddö, which provided unique insights into maritime mobile network usage patterns.

These base stations revealed distinctive characteristics of mobile network usage, particularly during ship passages. The analysis showed that while residential users maintained a stable presence of 5-20 users per sector, ship movements created predictable, short-duration user spikes of up to 100+ users. These spikes correlated directly with ship movements across different base station sectors, demonstrating the dynamic nature of maritime network connectivity.

Interestingly, the data revealed that peak user numbers did not always correspond to high data consumption, suggesting complex user behavior and potential variations in onboard communication strategies. This local-level analysis provides critical ground-truth data that complements the broader route-based measurements, offering a more nuanced understanding of maritime network performance in the Åland archipelago.

Conclusion of the case study

The Naantali-Kapellskär case study demonstrates the promising potential of using mobile networks for maritime communications in the Finnish-Swedish archipelago. While the current infrastructure shows considerable capabilities, the research underscores the need for continued optimization and the development of hybrid connectivity solutions to fully support autonomous and remotely controlled vessel operations.

Dynamic Time Division Duplexing

Dynamic Time Division Duplexing (Dynamic TDD) is a key feature in 5G networks that enables the network to adaptively adjust uplink (UL) and downlink (DL) time slot allocations based on real-time traffic demands. This flexibility is particularly advantageous for remote operations, where uplink data transmission requirements may fluctuate significantly. By dynamically allocating additional uplink slots when necessary, the network can efficiently accommodate high volumes of data generated by remote devices and transmitted to central control systems.

However, the implementation of dynamic TDD demands meticulous coordination to mitigate the risk of cross-link interference (CLI), which arises when adjacent cells operate with conflicting UL and DL schedules. Effective synchronization and robust interference management strategies are therefore critical to ensuring consistent network performance and operational reliability, especially in high-density or industrial settings.

In the maritime domain, remote operations such as the control of autonomous vessels and the monitoring of maritime equipment rely heavily on dependable and responsive communication infrastructures. The configuration of appropriate UL and DL data rates is essential to facilitate these operations effectively. Potential uses of Dynamic TDD for autonomous vessels are presented below.

Autonomous vessels - strict uplink data rate requirements

Autonomous maritime vessels are equipped with a variety of onboard systems—including sensors, radar, and high-definition cameras—which generate substantial data to support navigation, situational awareness, and operational monitoring. As a result, uplink requirements for such vessels can range from 10 Mbps to over 100 Mbps, depending on the number and resolution of video feeds and sensor streams.

Conversely, downlink needs are generally more modest but nonetheless vital. These include the transmission of navigational instructions, control commands, and software updates from the shore-based command center to the vessel. Downlink speeds typically range from 1 Mbps to 10 Mbps, contingent upon the complexity and frequency of transmitted commands. Thus, the data requirements for uplink and downlink are rather reversed as compared to the normal use in the cellular networks.

Port Operations – strict latency requirements

In port environments, 5G connectivity has enabled significant advancements in automation and operational efficiency. Automated Guided Vehicles (AGVs) are widely deployed for transporting cargo containers. Trials have demonstrated that 5G networks can reduce latency to as low as 10 milliseconds, approximately 50% lower than typical 4G network performance. This low latency allows AGVs to operate with greater precision and responsiveness, which is crucial in spatially constrained and safety-critical port environments[2].

Automated Rubber-Tired Gantry Cranes rely on high uplink throughput to transmit real-time video streams from crane-mounted cameras to remote operators. When leveraging millimeter-wave frequencies within 5G networks, uplink data rates have exceeded 140 Mbps, with latencies maintained below 50 milliseconds. These capabilities enhance the reliability and effectiveness of remote crane operations[3].

Generally, minimizing latency is crucial in maritime applications, particularly those involving real-time control, as it ensures timely decision-making and immediate system responsiveness. Equally important is the reliability of the communication link, which must be robust enough to prevent operational disruptions that could compromise both safety and efficiency. Furthermore, maintaining continuous and comprehensive connectivity presents a distinct challenge in maritime settings, especially in open sea regions where terrestrial networks are not available. In such cases, satellite communication systems are typically employed to bridge these connectivity gaps and maintain consistent communication with maritime assets.

Regulatory framework

The regulatory framework for maritime mobile networks requires a comprehensive approach that addresses cross-border communication challenges, spectrum management, and technological innovation. There is a critical need for harmonized communication regulations that span maritime territories.

There are several potential spectrum management strategies for the MNOs to enhance maritime network performance, as the regulatory environment is technology neutral. These include the potential repurposing of existing spectrum, such as spectrum currently used for digital terrestrial television, converting the 800 MHz band to 5G, and transforming the 900 MHz 3G band for 5G use. By carefully utilizing these frequency bands, mobile network operators can provide more robust and consistent mobile network coverage in maritime environments.

Increasing base station power could improve the network coverage in areas with sparse coverage. This should be taken into account in the regulation. To better support the uplink heavy remote operations and emerging maritime digitalization, the network operators could optimize the configurations including the TDD uplink/downlink ratio. Based on the measurements on this specific route, the basic coverage of the mobile networks is fairly good, but we should remember that this route is very specific, due to archipelago. Other routes on open sea will have less comprehensive coverage.

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[2] Infocomm Media Development Authority. *5G Use Case Trials in Port Operations*. IMDA, Oct. 2021, www.imda.gov.sg/-/media/Imda/Files/Programme/5G-Innovation-and-Grant/IMDA-5G-Use-Case-Findings_PSA.pdf
[3] Natrajan, Nikhila, and Trisha Ray. "Indo-Pacific 5G survey: Connections and conflict." (2021).

Conclusions

The ADMO project demonstrated the promising potential of mobile networks for maritime communications, particularly in archipelagic regions like those between Finland and Sweden. Comprehensive measurements show that lower frequency bands (below 1 GHz) provide the most consistent coverage in maritime environments, with RSRP values consistently better than -90 dBm across nearly 100% of the coastal route, while higher frequency bands offer enhanced capacity near coastal areas.

Despite achieving excellent signal strength along most of the route through strategic base station placement on islands, capacity limitations remain a significant concern. Based on feedback from vessel operators, network congestion already occurs during peak usage periods, suggesting that while coverage may be adequate, available bandwidth may not meet the growing demands of maritime applications. This is particularly problematic for remote operations that require substantial uplink capacity for video feeds and sensor data transmission.

Our analysis indicates that current connectivity levels are sufficient for basic remote monitoring and automated navigation systems that require modest data rates (1-5 Mbps), but insufficient for advanced remote operations requiring real-time high-definition video transmission (>10 Mbps uplink). Different maritime functions have varying connectivity requirements - safety-critical systems require consistent but moderate bandwidth with high reliability, while operational efficiency applications can operate with more variable connectivity but may need higher peak data rates. This suggests a tiered approach to maritime connectivity solutions rather than uniform high-capacity coverage across all areas.

Additionally, minor coverage gaps persist in open sea areas between Åland and the Stockholm archipelago. Hybrid connectivity solutions that integrate satellite communications with terrestrial networks would ensure continuous connectivity and improved capacity for critical maritime operations. While signal strength provides a good indication of network coverage, it does not necessarily correlate with available capacity in maritime environments, where many vessels may be competing for the same network resources. This distinction is crucial when evaluating network suitability for bandwidth-intensive applications.

Terminal-side technical solutions can significantly improve maritime connectivity without requiring extensive network upgrades. Carrier aggregation across multiple sub-1 GHz bands could enhance data rates while maintaining good coverage, and advanced MIMO configurations on vessels can improve signal quality. Creating dedicated WLAN networks inside vessels connected to external high-gain antennas would optimize the use of available signals and allow for more efficient local data distribution. Our measurements suggest that such configurations could increase effective throughput significantly in marginal coverage areas.

Port environments present unique opportunities for enhanced connectivity through dedicated local networks. High-capacity, short-range technologies like Wi-Fi 6E or private 5G networks in ports could provide vessels with reliable high-speed connections during docking, enabling large data transfers for maintenance updates, passenger connectivity, and operations data synchronization. These short-range but high-capacity connections would complement the more widespread but lower-capacity offshore coverage.

Future network developments, including 5G Advanced 3GPP's Release 18 with Non-Terrestrial Networks (NTN) capabilities, advanced sidelink communications, and enhanced hybrid connectivity options, promise significant improvements for maritime communications. These advancements could help address both the coverage gaps and capacity limitations identified in our measurements.

While regulatory measures can support maritime connectivity development, market-driven approaches likely offer more immediate and sustainable solutions. Increased base station power in sparse coverage areas represents a targeted technical solution rather than broad regulatory change. The suggestion for frameworks supporting maritime mobile base stations addresses the unique challenge of providing connectivity in areas too far from shore for fixed infrastructure but frequently traveled by vessels. This could create new business models for Mobile Network Operators (MNOs) to serve maritime customers more effectively through vessel-mounted base stations that extend network coverage.

When compared with traditional maritime communication systems like Global Maritime Distress and Safety System (GMDSS), Very High Frequency (VHF) radio, and Automatic Identification System (AIS), modern cellular networks offer significantly higher data rates and lower latency, essential for next-generation maritime applications. As detailed in ADMO Deliverable 2.1 - Report on the state-of-the-art of the ship external connectivity, while these traditional systems provide reliable basic connectivity with typical data rates of several kbps, they cannot support the megabit-per-second requirements of autonomous operations and remote control. However, they remain valuable as complementary systems, particularly for safety-critical communications due to their robustness and dedicated spectrum. A strategic integration of both traditional and cellular systems would provide optimal resilience and performance.

The inherent asymmetry between uplink and downlink capacities in commercial mobile networks presents a particular challenge for autonomous and remotely controlled vessels. As our findings indicate, even where signal strength is excellent, the uplink-heavy requirements of maritime applications may exceed what current networks, optimized for consumer downlink usage, can provide. Future maritime-specific network deployments may need to consider significant uplink optimization to support the data transmission needs of autonomous vessels.

The project's findings provide valuable insights for designing robust communication systems for autonomous and remotely controlled vessels, establishing clear performance requirements across different use cases, and creating a roadmap toward fully digitalized maritime operations. Further work should focus on application-specific performance testing and developing intelligent network selection algorithms that can optimize connectivity based on both signal strength and available capacity.