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Optimizing Satellite Communication for Maritime Autonomous Surface Ships (MASS) Monitoring: Overview of the Role of Age of Incorrect Information in Preventing Data Channel Congestion

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Abstract. Maritime Autonomous Surface Ships (MASS) represent a major advancement in the shipping industry, however their safe and efficient operation depends critically on reliable communication, particularly over satellite links on the high seas. This paper provides an overview of the challenges associated satellite-based communication for MASS and discusses how data-relevance-based performance indicators such as the age of incorrect information (AoII) can help optimize data exchange. Our paper outlines how these principles can support situational awareness, minimize communication latency, and improve resilience during signal degradation or loss. This approach helps ensure that remote operators and autonomous decision systems receive accurate, actionable information when it is most needed. The paper highlights AoII as a promising criterion for protocol design and optimization to manage communication within the growing ecosystem of MASS.

1. Introduction

Maritime autonomous surface ships (MASS) are one of the next significant advancements in shipping technologies, offering a broad range of new possibilities. With the further advancement and research in this area, more challenges are being tackled. The requirements for safe and reliable operations of MASS are becoming clearer and are getting defined by, e.g., class societies or the International Maritime Organization (IMO) [1–4]. One important building block to enable these technologies will be the communication with MASS [4–6], especially the reliable data exchange between ship and shore [5, 7]. For all MASS degrees of autonomy defined by IMO the reliable exchange of data is crucial for safe operation [6]. In many ways the Industry 4.0 is being more and more used onboard ships in recent years [7, 8]. Many of the technologies like digital twin, predictive maintenance and more data driven technologies depend on a steady stream of data [8]. Unlike the counterparts of industry on land, the maritime domain has its own challenges in regard to connectivity and data transmission and must find solutions to enable this step. For MASS these challenges are increased, since they are more dependent on reliable connectivity for safekeeping or navigation than other vessels [1, 5]. The need for different communication channels like 4G/5G, VHF Data Exchange System (VDES) or satellite will arise, and the different connectivity options will interlink more to always choose the best option available [9, 10]. On the



high seas however, satellites are the only available option to communicate on a global scale. In the past, satellite connectivity in high seas was mainly delivered via geo-stationary links [9]. However, with recent developments in terms of low Earth orbit (LEO) constellations, like Starlink or Kuiper, nowadays there are more possibilities for satellite connectivity [7]. To manage the information throughput and maintain an up-to-date tracking of the status of ships at sea, different methods can be applied and further explored. In this paper we discuss a promising approach for protocol design and optimization, based on the notion of data-relevance and considering the age of incorrect information (AoII) as a performance indicator.

In this remainder of the paper, we first highlight the importance of an available communication channel for MASS, then we give an overview of the dependence on satellite connections of MASS. We introduce the AoII metric and give an overview how it can help to mitigate possible satellite connections and deliver information in a timely manner. As this paper focuses on the conceptual integration of AoII in satellite communication for MASS, it does not include experimental validation, as the approach is still in early development. The aim is to provide a foundation for future applied research and practical trials. Finally, we discuss the possible value of AoII and give an overview of where it can help in MASS applications.

2. Importance of Communication for MASS

A successful implementation and operation of MASS hinges upon several key aspects, one of them being communication among MASS [1, 3]. In the context of autonomous vessels, communication can be seen not as merely a supportive function, but rather as a fundamental enabler for the exchange of information in real-time. This is in turn essential to allow autonomous ships to perceive, interpret, and respond to their operational environment with a level of situational awareness to ensure safe operations at all times [11]. The IMO defined four stages of autonomy that require different monitoring and handling from human operators [6]:

- **Degree one:** Ship with automated processes and decision support. Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control.
- **Degree two:** Remotely controlled ship with seafarers on board. The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions.
- **Degree three:** Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location.
- **Degree four:** Fully autonomous ship: The operating system of the ship is able to make decisions and determine actions by itself.

Depending on the degree of autonomy, the communication needs will differ in their intensity and in what has to be transmitted, but arguably for the first three the need for real-time communication will rise from degree to degree, in particular to guarantee situational awareness. For MASS, situational awareness must be constructed through a network of interconnected systems and platforms. These may include onboard sensors, satellite data, shore-based control centers, other vessels, and maritime authorities. The effectiveness of these systems depends not only on their individual accuracy but on their ability to share and update critical information in real-time. This requirement elevates communication to a strategic function. Latency, bandwidth,

redundancy, and interoperability across different platforms and protocols become central considerations. Any lapse in the continuity or integrity of data exchange could result in degraded decision-making, increased risk of collision, or failure to comply with navigational regulations and dynamic environmental conditions. Furthermore, real-time communication supports collaborative autonomy, wherein MASS interact not only with their environment but also with other autonomous or conventionally manned vessels. This cooperation, particularly in congested or high-traffic waterways, demands robust communication frameworks that can support dynamic negotiation, intent-sharing, and coordinated maneuvers. For this communication in MASS must be viewed through the lens of timely, reliable, and secure information exchange that sustains situational awareness for the human operator or for the MASS itself and supports autonomous decision-making.

3. Satellite connectivity at sea

Reliable communication at sea has long posed significant challenges due to the absence of terrestrial infrastructure across the ocean. The evolution of satellite technology has played a pivotal role in bridging this gap, enabling global maritime connectivity. Historically, satellite communications began with geostationary Earth orbit (GEO) satellites, positioned approximately 35,786 kilometers above the equator [9, 12]. These satellites offer wide coverage and have been the backbone of maritime communications for decades, supporting applications such as voice transmission, distress signaling, and later, low-bandwidth internet services [9]. However, due to their high altitude, GEO satellites suffer from high latency (typically around 240 milliseconds round-trip time) and typically offer limited bandwidth to MASS systems, which constrains performance for modern, data-intensive applications [9, 12]. In response to these limitations, the industry has progressively shifted toward lower altitude satellite constellations. Medium Earth orbit (MEO) satellites have offered improvements in latency and throughput. However, the most transformative development has come with the deployment of low Earth orbit satellite constellations. Operating at altitudes between 500 and 2,000 kilometers, LEO satellites significantly reduce latency and enable much higher data rates. Companies such as SpaceX (Starlink), OneWeb, and Amazon (Project Kuiper) have launched or are in the process of deploying massive LEO constellations, targeting continuous global coverage, including remote oceanic regions [8]. These systems represent a substantial shift in maritime communication capabilities, supporting real-time video, VoIP, telemedicine, IoT applications, and seamless crew welfare connectivity. Currently, there are no viable alternatives to satellite-based communication for maritime applications [12]. High Altitude Platform Stations (HAPS), such as stratospheric balloons and solar-powered drones, have been proposed as potential substitutes [9]. These platforms aim to provide regional coverage with lower latency and greater responsiveness. Nevertheless, HAPS remain largely experimental, with few implementations beyond limited trials [9]. The technological, regulatory, and operational challenges of sustaining HAPS over open oceans—such as weather resilience, power supply, and long-term station keeping—have prevented their deployment at scale [9]. Thus, satellites continue to be the only practical and globally available solution for high-sea connectivity. The transition from GEO to LEO architectures marks a significant evolution in performance, scalability, and accessibility, laying the foundation for a new era of digital transformation in the maritime sector.

The reliance on satellite communication for MASS comes with its own challenges, especially when MASS start to scale and when more and more MASS units are in use. On the other hand, with the increase of applications on MASS more data will be transmitted and the challenges might be

concerning for MASS, but are not limited to them and can affect crewed vessels as well. One of these challenges will be the potential congestion of satellite connections in dense shipping areas and the implication of information loss associated with it. Such a problem already affects the Automatic Identification System (AIS) satellite signals. In dense sea traffic corridors, AIS signals transmitted from thousands of ships often interfere with each other and overwhelm the limited channel capacity of satellite receivers. This leads to delayed, lost, or incomplete data retrieval, undermining real-time situational awareness and vessel coordination [13, 14]. This example epitomizes a broader concern about LEO satellite network saturation, particularly if looking at the dependence on these connections for MASS. The same principle applies—at a much larger scale—to LEO satellite communication networks that MASS will rely on. Unlike AIS, which transmits short bursts of navigational data, autonomous ships will continuously exchange numerous amounts of data, latency-sensitive information for navigation, remote monitoring, diagnostics, and coordination with other vessels and control centers. In traffic-heavy regions like the English Channel or the Strait of Singapore, hundreds or thousands of MASS units could simultaneously demand stable satellite links. While to serve high-capacity services like video-streams the main option is an increase in bandwidth, provision of lower data rate but massively generated information flows can be efficiently targeted by devising advanced communications protocols. Just as AIS satellites struggle to manage high-density signal environments, LEO satellites risk beam saturation, uplink congestion, and interference when servicing tightly clustered autonomous fleets [12]. In this perspective, without careful protocols optimization, and integration of edge processing or hybrid networks, LEO systems supporting autonomous maritime operations may face similar or even more severe performance degradation.

4. Data-relevance and age of incorrect information

As argued in the previous sections, the increase of traffic and MASS connectivity via satellite calls for an improvement of communication protocols. From this standpoint, existing solutions are typically designed and optimized under the lens of traditional performance indicators such as throughput, data rate, reliability, and latency. While properly describing the efficiency attained in utilizing a communication channel, these metrics often fall short in capturing the ability to maintain an up-to-date perception at the final point of monitoring of the state of a transmitter which is sending updates [16] — a key enabler for MASS operation. On the other hand, many practical solutions for maritime data exchange were not originally thought for satellite connectivity, and may not reach the intended performance targets when vessel data is gathered over the vast coverage range provided by non-terrestrial networks. A relevant example in this direction is provided by the transmission of AIS messages, with ships exchanging information following a self-organizing time-division multiple access protocol. The scheme was devised for communication among small clusters of vessels within visibility of each other, or close to port areas, and allows an efficient delivery of data in such contexts. However, as soon as thousands of ships within a satellite beam rely on this solution, reception at the flying platform is severely affected by interference among non-coordinated clusters, resulting in poor performance and hindering a proper tracking of the status of vessels.

To tackle these challenges, a promising direction is to leverage the notion of data relevance [17]. In this respect, the key observation is that what matters most in MASS applications is the ability for a monitoring agent (be it a vessel, a port authority, or any other actor in the controlling process) to timely and accurately track the state of vessels. To characterize this ability, a number of metrics have recently been proposed, with a pivotal role played by the notion of age of

information (AoI). Originally introduced in vehicular communications systems [18, 19], the AoI at time t experienced by a monitor tracking a source of interest is defined as the difference between the current time and the time at which the last received update from the source was generated. In other words, the metric describes how old or outdated the available knowledge is. By virtue of its definition, AoI is a key enabler to evaluate timeliness, yet is oblivious of the value contained in the received updates, i.e., it does not consider how informative these may be. To go beyond this limitation, other indicators can be targeted and have been studied in recent literature. These include the value of information (VoI) [20], quantifying how relevant a received piece of information is towards a task of interest; the false alarm or missed detection probabilities [21, 22], identifying if a critical condition is missed or erroneously inferred; the uncertainty at the monitor on the state of a source [23, 24], often quantified in terms of entropy; as well as other metrics, e.g., [25, 26].

An indicator of particular interest for the present paper is the age of incorrect information (AoII). The metric can be seen as a penalty, taking value zero (no penalty) as long as the estimate available at the monitor can be considered correct (e.g., is within a tolerance of the true value of the source status), and growing linearly with time during periods in which the available knowledge is erroneous (e.g., due to a change of state that has not been notified successfully). The quantity was originally introduced in [27], and an example of its time evolution is reported in Fig. 1. For the given definition, it is common to consider the average AoII over a period of interest or the peak AoII (i.e., the maximum value it reaches before being reset) as performance criteria. In this respect, AoII can provide good insights on the behavior of a MASS monitoring system: on the one hand, it captures the aim of maintaining an accurate perception of the state of a vessel, and, on the other hand, it penalizes more longer periods of time affected by inexact knowledge, which may indeed lead to wrong operating decisions and dire consequences. Moreover, the metric leans on a simple definition, allowing for mathematical modeling as discussed for example in [14], and does not rely on the knowledge of the statistics of the process being tracked, resulting in a convenient proxy to gauge accurate and timely knowledge.

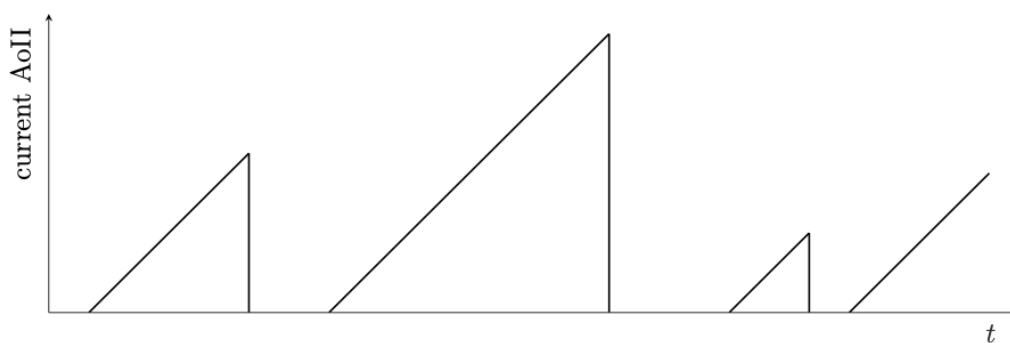


Fig. 1: Example of evolution over time of AoII. Whenever the estimate available at the monitor is accurate enough, the penalty is zero. As soon as the estimate becomes inaccurate, the metric grows linearly with time, being reset to zero upon reception of a new informative update.

5. Discussion

As discussed, satellite communications are a primary enabler for MASS, especially for long-range operations beyond the reach of terrestrial networks, yet they trigger significant challenges in the ability to maintain the timely and accurate knowledge required for MASS decision-making and situational awareness. To mitigate these issues, we advocate in this paper the use of data-relevance indicators, such as AoII, for the design and evaluation of next-generation maritime communication protocols. The notion of data-relevance allows systems to prioritize transmissions based on the importance of information, rather than accounting only for recency alone, or than sending data at fixed rates without notion any of the context. For example, if the ship's environmental sensor data (such as obstacle location or sea state) has not changed significantly, older but still-valid data can continue to be used without critical degradation of the information. Conversely, if an obstacle is detected or another vessel unexpectedly alters course, updates shall be exchanged to maintain reliable situational awareness. By relying on communication protocols designed to embed such principles, MASS can more intelligently manage the limited bandwidth of satellite channels and relay information that is more pertinent to shore based systems. Instead of streaming all data continuously at uniform rates, the system can adapt transmission frequencies to focus on the most decision-critical updates. This approach reduces channel congestion and increases the effective throughput of actionable information, which is particularly valuable in scenarios where multiple autonomous vessels share the same satellite resources. First steps towards demonstrating such potential were taken in [14], focusing on the specific case of AIS messages received by a LEO satellite. The analytical characterization of average AoII provided in the work is then instantiated in results that resort to real data for ship distribution and transmission rates. Leaning on this, it was shown how the plain AIS transmission policy can result in very high values of AoII, corresponding to outdated and imprecise knowledge available at the satellite (and thus at the final monitoring point). Instead, substantial improvements were demonstrated by resorting to a communication policy that triggers an update transmission only in case of a change of status (representing a significant variation of one or more of the relevant parameters for a MASS). The approach can easily be implemented, and does not require additional complexity at the vessel side (which only needs to keep track of the last sent values and employ a threshold policy to decide whether to attempt a further delivery) nor at the receiver side (which simply benefits from the reduced interference level enabled by the solely relevant transmissions). Along this direction, we remark that the use of AoII as performance indicator allowed to pinpoint a limitation of the existing approach, and to suggest simple yet more effective solutions. We thus argue that considering such metrics and design principles may be of particular benefit to next-generation MASS systems and shall be accounted for in the upcoming standardization efforts.

6. Conclusion

As the maritime industry advances toward broader deployment of MASS, ensuring reliable communication emerges as a critical factor in supporting safety, autonomy, and efficiency. Satellite communication remains the only viable solution for global maritime connectivity, particularly on the high seas. However, growing data demands and the scaling of autonomous fleets present serious challenges in terms of the amount of data, latency, and data prioritization. In this paper,

we consider how the use of data-relevance performance metrics, epitomized by the AoII can be a practical approach to mitigate these challenges. In particular, by linking data transmission not solely to timestamps, but to the contextual importance and accuracy of the information itself, the principles of data-relevance can lead to substantial improvements in communication protocols. This dynamic prioritization is particularly vital in time-sensitive, safety-critical scenarios where decisions rely on up-to-date, valid data. By integrating metrics such as the AoII into the design and optimization of satellite communication strategies, MASS can better manage the degradation of satellite channels, reduce channel congestion and interference, and favor the timely delivery of information. Continued research and standardization will be essential for practical implementation, in order to implement such concepts into next-generation MASS satellite connections.

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