IoT

Article

Full-Scale Assessment of the "5GT System" for Tracking and Monitoring of Multimodal Dry Containers

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Abstract: A novel tracking and monitoring system for ISO 668 dry containers was realized by the ESA-funded "5G SENSOR@SEA" project, integrating 5G cellular technologies for massive Internet of Things with a GEO satellite-optimized backhauling link. The scope is the development of monitoring and tracking new services for multimodal container shipping. With the cooperation of four industrial partners and a telecommunication research center, the so-called "5GT System" was designed, developed, tested and validated up to field trials. Several modules of the system were designed, built and finally installed on the ship and in the teleport: the container tracking devices placed on the containers, the NB-IoT cellular network with optimized satellite backhauling, the Ku-band satellite terminals and the maritime service platform based on the OneM2M standard. The field trial conducted during the intercontinental liner voyage of a container ship showed primary technical achievements, including fair switching between terrestrial and satellite networks, reduction in packet loss in the open sea scenario and seamless integration of the BLE mesh network over the container tracking devices as NB-IoT/BLE LE Mesh gateways.

Keywords: NB-IoT; non-terrestrial networks; Bluetooth low-energy mesh; container logistics; maritime transport

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1. Introduction

Maritime container traffic is the backbone of international trade and has reached an impressive size and number in recent decades. Dry containers are used to move 75 percent of global goods, and in 2021, according to UN trade statistics, 851.1 million twenty-foot equivalent units (TEUs) of containers were handled in ports worldwide [1]. Container shipping is by far the most economical and effective way to move goods over long distances. It is made possible through collaboration among a range of players (shipping lines, freight forwarders, shipping and customs agents, terminal operators, public institutions and ancillary service providers) and the use of shared tools, practices and standards. Digital technologies are spreading rapidly in this sector, bringing significant economic and environmental benefits. Major shipping companies have identified continuous container tracking and monitoring as key tools for increasing the reliability of shipments and generating important economies of scale. Equipping all containers with an Internet-connected tracking device is necessary in the global shipping market that is still waiting to be met.

The "5G Smart Edge Node and Smart Objects enabling Reliable Services Extended All over the seas" (5G SENSOR@SEA) project [2], funded by the Artes 4.0 program of the European Space Agency, addressed this need and aimed to realize a low-cost tracking and monitoring system for ISO 668 dry containers that integrates 5G cellular technologies for massive Internet of Things (IoT) deployment with GEO satellite link in a Ku-band-optimized backhauling function.

1.1. Objectives

The objective of 5G SENSOR@SEA is to design, deploy and evaluate the "5GT System" solution (5G Global Tracking System), constituted by an NB-IoT framework on top of a hybrid cellular-satellite network, providing real-time information coming from cargo-containers to a OneM2M IoT platform [3]. This continuous monitoring of cargo containers is performed across seas in a port-to-port service scenario, even in deep-sea travel.

The 5GT System also includes part of the network functions (especially related to satellite networks) deployed in the cloud as virtualized functionalities, thereby fostering higher cost efficiency for network deployments. Cloud virtualization technology and Software-Defined Networking (SDN) capabilities ensure the seamless integration of the satellite components in the upcoming 5G network systems.

Moreover, the satellite component of the 5GT System includes an onboard satellite transmitter using a protocol which includes a packet optimization module.

The objectives of this experimental research are to compare the communication performance of the system in terms of latency and message loss in the different operational contexts, i.e., when the containers are ashore in the yard, on the ship near the coast, and on the ship in the open sea. Furthermore, another goal is to validate the reliability of the operation of the whole system through a field trial involving an intercontinental liner cargo ship.

1.2. Benefits

Maritime transport is an ideal solution for those who have to transport large quantities of goods (raw materials, products of various kinds, energy resources) over long distances, without urgency and in an economical way. The logistic path of goods, which must be shipped by sea, is multimodal and involves sea and land transport. Generally, it can be summarized in four steps:

1. The goods are packed according to their nature, shape and size and then loaded into containers;
2. The containers are moved via land (by road or rail transport) from the loading hub to the port, passing through the customs of the point of origin;
3. After the Customs Agency, the containers are loaded on merchant ships;
4. Once they reach the port of destination, the containers pass through the Customs Agency again and are then released and delivered to the unloading hub. The goods are ready to be delivered to the recipients in a last-mile transport logic.

There are, however, some weaknesses. An example is the control and integrity of the goods; the containers are not protected from tampering or theft, so the recipient checks directly upon delivery whether their goods are intact. Risk is also a factor to consider. Ships can suffer the effects of fires onboard, adverse weather events, loss of containers, etc. Furthermore, when cargo is travelling by sea, it can be very difficult to monitor its progress and condition.

In this context, the 5GT System, combining GEO satellite technologies and the 5G cellular technology for the massive IoT, makes it possible to connect devices on a centralized cloud network by acquiring and sharing data in real time, with the advantage of obtaining constant and continuous monitoring along the entire container supply chain, involving various means of transport, maritime terminals and intermodal hubs.

Existing solutions are not capable of real-time communication for all dry containers carried by ships, which is why applied research in this field is still very active (see Related Work section). The approach proposed by the 5GT System outperforms the existing solutions because it introduces the 5G technology for the massive IoT that can effectively provide communication to a large number of devices. In addition, the architecture of the system avoids technology lock-in and ensures interoperability in the global supply chain marketplace. This is achieved by adopting standard reference technologies for machine-to-machine (M2M) communication, such as 3GPP for NB-IoT cellular networks and OneM2M for the maritime service platform. Thus, a horizontal layer with open and standard API is available for the further development of third-party applications. The tiered architectural approach and its related standards are shown in Figure 1.

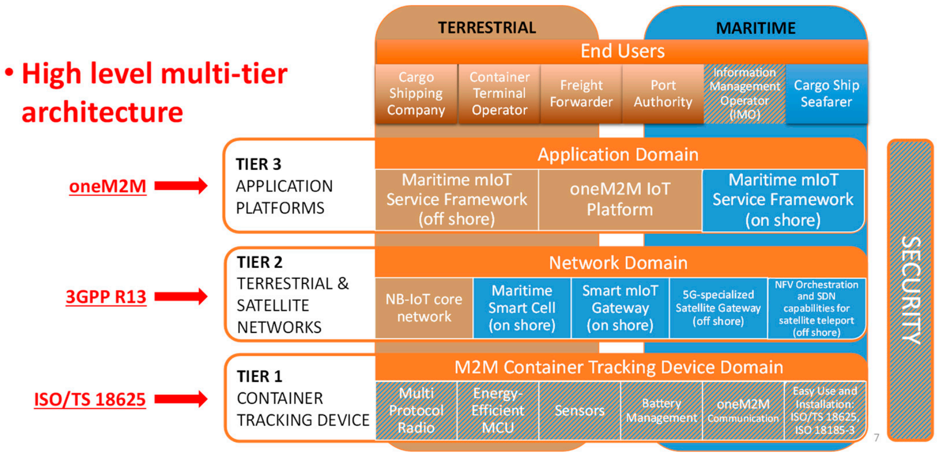


Figure 1. 5GT System architecture mapped to reference standards [3–5].

1.3. Partnership and Stakeholders

The 5GT System was built by a team of engineers from Italian companies (TIM, Azcom Technology, MBI, Sistematica) and a research laboratory (CNIT) at the forefront of innovation projects dedicated to the integration of 5G satellite and cellular networks. In particular, CNIT, which conceived the system and organized the activities, pursues the mission of technology transfer in port and maritime transport areas recognized by relevant grants from national (ASI) and European (ESA, ETSI, etc.) bodies. The technology phase of the 5G SENSOR@SEA project has received support from first-rate stakeholders: the Port Authorities of the Northern Tyrrhenian Sea and the Eastern Adriatic Sea, Eutelsat, and the shipping company Ignazio Messina &C. SpA, which hosted the tests in navigation on its transcontinental liner container ships.

1.4. Outline of the Present Paper

The industrial research work presented in this study will show how the "5GT System" was designed, developed, tested and validated up to field trials.

The contribution of this work is the following: Section 2 provides an overview of the enabling satellite technologies and related works. Section 3 presents the materials and methods for realizing the 5GT System. Section 4 describes the results of the validation in an operational environment. Finally, Section 5 contains concluding remarks and future applied research directions.

2. Enabling Satellites Technologies and Related Works

The reference scenario is the use of space systems/data for IoT applications, particularly in support of transport management and the development of intelligent transport systems.

In this scenario, the use of satellites for M2M/IoT applications enables reaching remote and widely scattered geographical areas (maritime, aerial, railway, vehicular) to connect devices with high mobility characteristics. Satellite M2M/IoT communications, either alone or as a complement to other terrestrial channels, can offer advantageous services for a range of applications:

- Addressing a massive number of devices simultaneously, for alarm management, triggering wake-up from deep sleep mode, and enabling other activities (e.g., software updates);
- Backup for terrestrial connectivity;
- Greater network control and independence from cellular operators;
- More stable and controlled Quality of Service (QoS), when low latency is not required;
- Very precise energy usage by end nodes;
- Ultra-low power transmissions are required due to regulatory constraints, i.e., RF emissions lower than some terrestrial solutions;
- Integration with GNSS data transmission applications;
- New services for platforms already connected via satellite (e.g., maritime platforms).

The types of IoT communication via satellite are of two kinds, either 'Direct Access' or 'Backhaul of Aggregated Sensors' (see Figure 2).

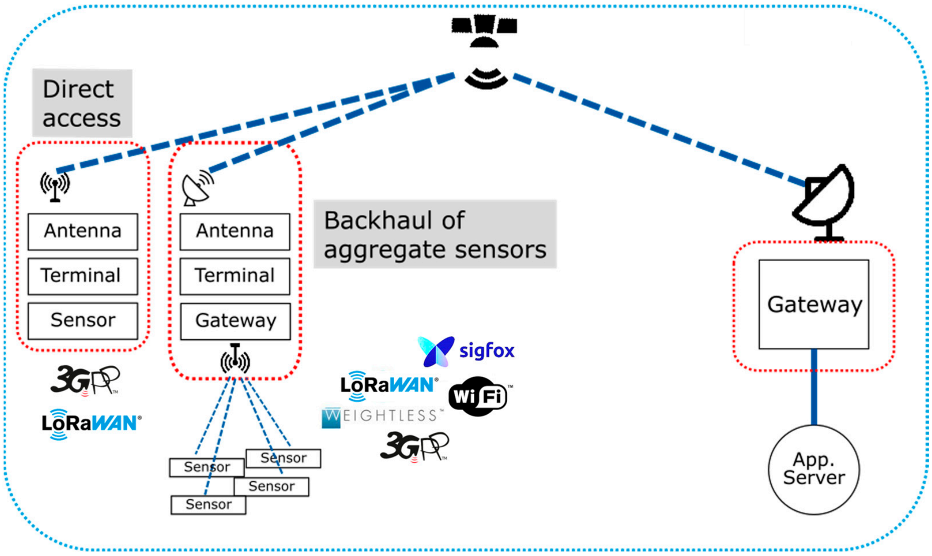


Figure 2. IoT via satellite topologies.

For each type, several solutions exist as the state of the art, some still at the prototype level, but also commercially evolved solutions [6]. For example, for direct access, some LEO satellite constellations dedicated exclusively to M2M/IoT equipment are already in orbit. Referring only to actual launches to date, there are 18 companies [7] that have put into orbit constellations of nano- and microsatellites for M2M/IoT applications. Among them, the main international initiatives by numbers and prospects are Swarm Technologies (US), Iridium (US), Orbcomm (US), Astrocast (CH), Sateliot (ES) and Lacuna Space (UK). To date, the first four companies offer commercial services, while the latter two do not yet offer paid services. Most of them are still completing their launch programs.

Direct-access communication protocols are based on several approaches, with some still under development. One approach is to repurpose standard protocols for terrestrial LPWA networks to satellite channel characteristics. For example, the possibility of using LoRa with low-orbit satellites was first analyzed [8,9] and, thus, demonstrated on some occasions (e.g., in 2018 during a conference held in Amsterdam, NORSAT-2, which normally transmits AIS information in the VHF bands, was modified to transmit LoRa messages [10]). These approaches are behind the industrial initiatives of the British firm "Lacuna Space" [11] and the German firm "Sat4M2M" [12], which, to date, do not yet offer a commercial service but are gathering interest and pre-orders from IoT solution operators.

Another approach in the same scope is to adapt standard NB-IoT protocols to satellite networks [13]. Mobile telecommunications standard 3GPP release 17 (March 2022) has brought a new set of capabilities, integrating 5G New Radio with satellite-based systems, effectively delivering narrowband IoT (NB-IoT and eMTC support) direct communications between satellites and cellular-enabled devices [14]. Presently, a commercial 3GPP R17 NTN RAN already exists [15], offering a service that allows NB-IoT cellular devices to connect directly over existing GEO satellites. Parallelly, the use of the LEO constellation for implementing direct 3GPP-compliant NB-IoT communication is still gaining efforts from both applied research [16–18] and the cellular industry [19]. In [16], a critical overview of the possibility of using NB-IoT over LEO, compliant with 3GPP specifications, is presented, and a novel service-oriented methodology is offered to design an effective solution, stitched around application requirements and technological constraints. In [17], a comprehensive state of the art of the development of the NB-IoT via NTN is reviewed. It was found that despite increased attention on the issue of congestion in LEO satellite networks, no effective algorithm has been proposed to address it while considering the limited visibility window of the satellites. To improve this, a novel twofold approach is suggested and evaluated with simulations: first, dividing the satellite's coverage area into Coverage enhancement Levels (CLs), with preambles assigned based on user visibility and transmission length; second, a smart backoff algorithm is introduced, allowing users to calculate a customized backoff interval, improving the efficiency of the random-access procedure. The NB-IoT4Space [18] project funded by the ESA and developed by an Italian team (including CNIT) developed a demonstrator, in which communication between an NB-IoT User Equipment (UE) and an eNB adapted according to the 3GPP standard for LEO satellite communications was functionally verified. Sateliot [19] is the first company to operate a Low-Earth Orbit (LEO) 5G IoT satellite constellation acting as a seamless roaming extension of cellular networks. It will launch four new satellites into space during 2024 with SpaceX [20]. Furthermore, a new launch and deployment services agreement was recently announced with Exolaunch [21]. With the deployment of these four satellites plus the two already orbiting the Earth, Sateliot enters the first phase of its constellation, moving towards the impending commercial phase.

Looking ahead, Rel-18 and Rel-19 3GPP will further extend the 5G outreach by including solutions to enable both NR-NTN and IoT-NTN in bands above 10 GHz to serve fixed and moving platforms (e.g., aircraft, vessels, UAVs) as well as building-mounted devices (e.g., businesses and premises) [22]. The goal of these efforts is to further optimize satellite access performance, address new bands with their specific regulatory requirements, and support new capabilities and services as the evolution of 5G continues. Further evolution of IoT-NTN is underway with a dedicated Rel-19 work item, focusing on support of Store & Forward (S&F) operation based on regenerative payload, including the support of feeder link switchover to guarantee the best possible uplink and downlink connectivity, especially in low-density constellations and even when visibility to a ground station is discontinuous [23]. With this innovative feature, IoT delay-tolerant applications can connect from day one and avoid the huge cost of mega-constellations.

Finally, again in the context of LEO direct access, mention should be made of Astrocast's network [24], based on a proprietary system developed from scratch together with Airbus and Thuraya, which differs from networks from other satellite providers that are trying to extend existing standards, such as LoRa and NB-IoT. Astrocast already offers a commercial service with global coverage, transmitting in the L-band by operating a constellation of LEO nano-satellites with a highly optimized protocol for IoT in terms of energy consumption and efficiency.

Regarding the other approach, i.e., using the satellite link as a backhauling function, a possible architecture was proposed by the so-called "MegaLEO" project [25] using three wireless network types—WSN, WLAN, and WWAN—to address maritime transport issues, such as cold chain monitoring, leveraging an IoT network supported by MEO satellites. The communication infrastructure involves Zigbee for WSN sensor networks, WiFi for communication with ship-based stations, and SatCom for satellite connectivity, integrating with the AIS protocol to improve system throughput and reduce latency compared to GEO satellites. The architecture and messaging system allow for dynamic ship route updates in the case of cold chain disruptions and can accommodate future expansions to monitor additional parameters like O_2/CO_2 levels and cargo volume. The inherent limitation of such an architecture is that WiFi networks and gateways for WSNs are also required ashore if containers are to be tracked not only at sea. In addition, although the guidelines issued by IMO (International Maritime Organization) and IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) do not exclude the possibility of the transmission of extended security messages (Application-Specific Messages), which can be used to provide additional information about cargo [26], the current AIS messages do not provide adequate protection against cyber threats and have several cybersecurity vulnerabilities. The AIS system was designed in the 1990s and was not originally conceived to deal with modern cyber threats, which is why it will be difficult for it to be adopted by maritime operators to communicate economically sensitive information about the status of containerized cargo.

The integration of more secure and up-to-date protocols in the "backhauling" approach was initiated by the ESA-funded IOT SATBACK project [27] (see Figure 3), which demonstrated a prototype of the E-SSA-based solution [28] for the backhauling NB-IoT network via the Ku-band. This technology has been further developed and integrated into the 5GT System for maritime transport services by the 5G SENSOR@SEA project [2], which completed the field-testing activities in April 2023. The "NB-IoT backhaul solution" offers a real-time connectivity solution for container traffic monitoring with global coverage that exceeds the current capabilities of direct access on low-orbit satellites. In addition, even ashore, containers continue to be monitored thanks to NB-IoT cellular coverage, which, among IoT LPWAN networks, is the most extensive globally and continues to expand rapidly [29].

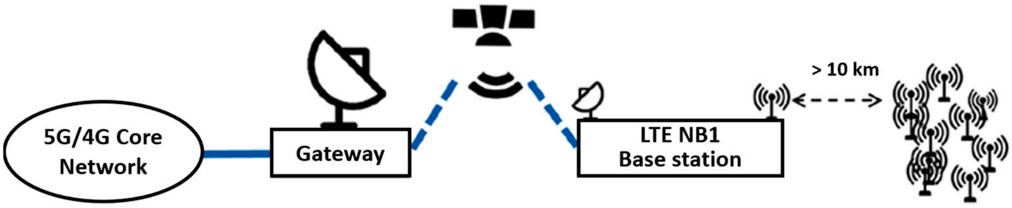


Figure 3. NB-IoT backhaul over satellite.

An updated review of recent work on applied research, enabling technologies and standardization initiatives in the scope of "smart containers", was presented in a recent article [30]. Since nothing newer has emerged in recent months, we refer to that article for a review of related work as of the date of writing this contribution.

3. Materials and Methods

3.1. Overview of the 5GT System

The 5GT System enables real-time and remote monitoring of the cargo ship container status and events during deep-sea journeys. It is constituted by an NB-IoT framework on top of a hybrid terrestrial-satellite network, providing information coming from the cargo-ship scenario (maritime domain) and port terminals (terrestrial domain) to a OneM2M IoT cloud platform, making them available to the user application, i.e., a dashboard which provides the status of the container to the customer (e.g., cargo shipping companies, port authorities, freight forwarders, etc.).

The 5GT System incorporates certain network functions, particularly those associated with satellite networks, which are deployed in the cloud as virtualized services. This approach enhances cost efficiency in network deployments. The use of cloud virtualization SDN technologies enables smooth integration of satellite components within the next-generation 5G network infrastructure. Additionally, the satellite component of the 5GT System features an onboard transmitter that utilizes a protocol incorporating a packet optimization module to improve data transmission efficiency.

An overview of the 5GT System is shown in Figure 4, a block diagram showing the contribution of each partner is in Figure 5 and the role of each component is reported as follows.

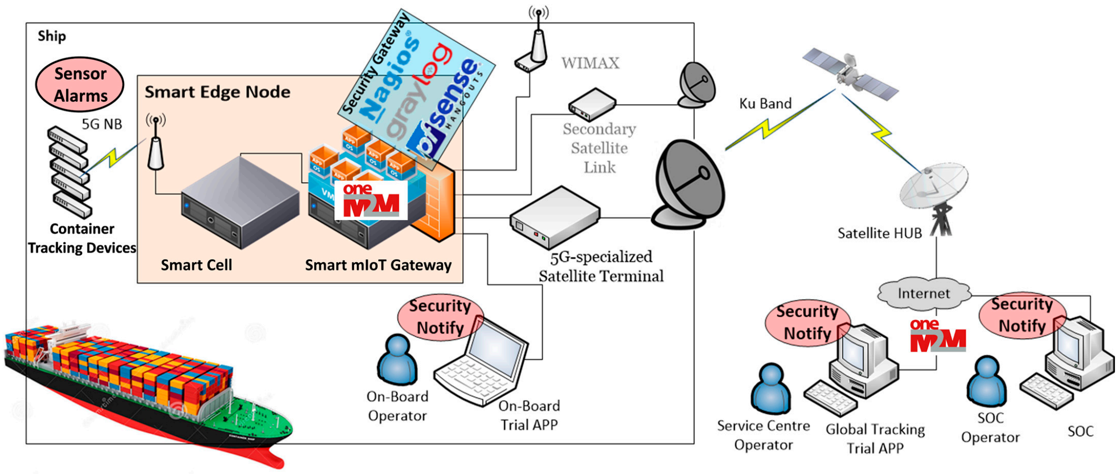


Figure 4. 5G Global Tracking System overview.

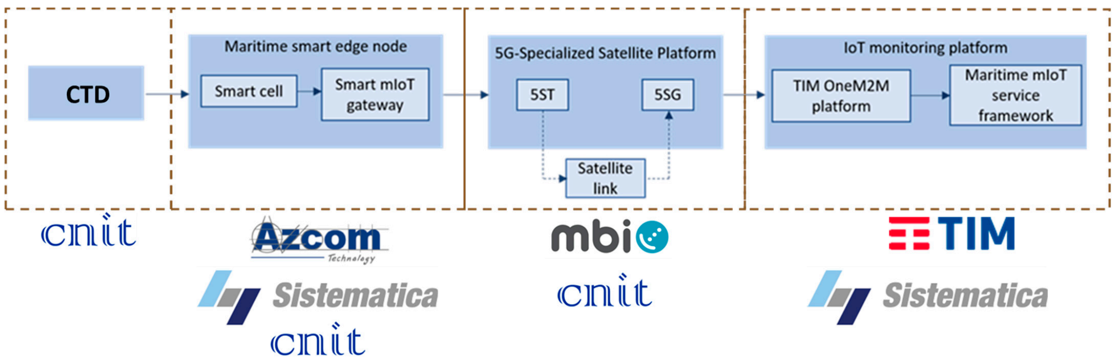


Figure 5. Block diagram of the 5GT System showing the contribution of each partner.

Container tracking device (CTD)—Through specific sensors and a GNSS receiver, it detects data regarding the container status and position. Two types of radio interfaces are available covering "long-range" and "short-range" communication: NB-IoT and BLE Mesh. Thus, it sends the data either via a cellular network or a mesh network; the second option works if the CTD cannot connect to the cellular network. In any case, data arrive at the cell base station either directly or via passes between mesh nodes to the CTD in cellular visibility. The operation of CTDs is the same in all scenarios (maritime and terrestrial).

Maritime smart edge node—The Smart cell is an NB-IoT cellular network installed onto the vessel onboard. The Smart mIoT gateway provides secure and reliable multi-backhauling connectivity for ship-shore NB-IoT data.

5G-specialized Satellite Platform—This is constituted by the 5G-specialized Satellite Terminal (5ST), a transceiver guaranteeing connectivity in the open sea via a Ku-band satellite link. On the ground side, the 5G-specialized Satellite Gateway (5SG) performs demodulation and Layer-2 functionalities.

IoT monitoring platform—It comprises the OneM2M platform and an application framework, namely the "Maritime mIoT Service Framework".

3.2. Key Features

A sophisticated communication network was deployed on a ship to enable seamless tracking and monitoring of cargo containers. Central to this setup is a radio base station operating on Band 28 (700 MHz), complemented by an NB-IoT core network. These components are connected via satellite backhauling, ensuring robust connectivity even in remote maritime environments.

Each container is equipped with a CTD that acts as a gateway between NB-IoT and BLE Mesh. This dual functionality ensures reliable communication, even when containers are densely packed, stacked in tight spaces, or placed in areas where cellular signals struggle to penetrate.

A key innovation is the deployment of a 5G-specialized Satellite Platform designed with satellite communication protocols optimized for NB-IoT. This platform ensures that data transmission between the ship and the satellite network is both efficient and reliable. To further enhance this system, Ku-band frequencies are employed for transmitting and receiving data. This frequency band is particularly advantageous in mobile scenarios, as it offers a more cost-effective alternative to traditional L-band frequencies. The reduced cost of Ku-band bandwidth makes it attractive to shipping lines, helping lower operational expenses. Moreover, this shift is beneficial for satellite operators without L-band licenses, enabling them to enter the IoT market, which has historically been dominated by L-band users.

The system leverages Eutelsat's GEO satellite constellations, known for their high service reliability. Compared to emerging LEO constellations, GEO satellites currently offer superior stability, making them an ideal choice for uninterrupted communication in maritime settings.

To ensure seamless integration between the satellite and cellular network components, SDNs are implemented. This approach enhances flexibility, allowing satellite resources to be dynamically integrated into 5G networks, thus improving overall network efficiency.

Finally, the system supports a range of tracking and monitoring applications for both onboard crew and shore-based stakeholders through a OneM2M-compliant platform. This standardized framework ensures interoperability between various IoT devices and networks, offering a cohesive user experience and enabling efficient cargo management across different environments.

This comprehensive solution not only improves operational efficiency for shipping companies but also reduces costs and opens new business opportunities for satellite operators, making it a valuable technological advancement in maritime logistics.

3.3. Container Tracking Device

The container tracking device (CTD) meets the project user requirements, including pre-compliance to ISO 668 [31] and ISO 18185-3 [4] standards for HW characteristics and ISO/TS 18625 [5] for operational and system requirements.

It is an electronic, compact, lightweight, battery-powered device to be installed on maritime containers by means of a suitable mechanical container and its attachment system. The function of the CTD is to monitor in real time the status of the container to which it is attached (externally on the door), regardless of geographical location (land or open sea). It has sensors (temperature, acceleration, pressure, humidity, anti-tampering of door opening) and two types of radio interfaces, covering "long range" and "short range", NB-loT and BLE Mesh, as well as a GNSS receiver for position and timing and a UHF RFID illuminator.

The NB-loT radio interface enables the CTD to connect to a radio base station (BS) installed onboard (when offshore) or to the land-based cellular network (in coastal territorial waters or at logistic terminals ashore). The presence of the BLE radio interface allows the various CTD devices in proximity (present within the BLE's coverage range) to establish a "mesh"-type connection in order to exchange mutual sensor status, especially when the condition occurs where some CTDs are located in areas not reached by the cellular signal. In this situation through the mesh network, it is possible to propagate data from a CTD, in sensor node configuration, to the CTD docked to the NB-IoT cell that assumes the role of gateway between the BLE and cellular networks.

Depending on the connectivity status of the radio interfaces, the device can assume the following roles:

- NB-IoT terminal
- BLE Mesh Node
- NB-IoT/BLE mesh gateway

The role of the device is dynamic and determined by the operating conditions. Each CTD can, therefore, assume various roles at different times. The role has no impact on either the hardware or the firmware of the CTDs, which are all the same.

The microcontroller firmware is designed to support a range of critical functions that enable real-time monitoring and secure management of cargo conditions. Among its primary features is the ability to read environmental sensors, including those that measure temperature, humidity, and pressure. This ensures that the system can continuously monitor and report on the environmental conditions of cargo containers, helping to maintain the integrity of sensitive goods.

Another essential feature is the monitoring of the RFID electronic seal. The firmware can read the seal's status, identifying whether it is tampered with, open, or closed. This capability enhances security by allowing for the instant detection of unauthorized access or breaches, ensuring that cargo remains secure throughout transit.

Additionally, the firmware integrates data from an accelerometer, enabling it to detect significant movements or shocks. This feature is particularly valuable for monitoring the handling of goods, as it can alert stakeholders to potential damage caused by rough handling or unexpected impacts during transportation.

The system also incorporates location tracking by reading geographic coordinates via a GNSS (Global Navigation Satellite System) module. This ensures precise real-time positioning, allowing for continuous tracking of cargo throughout its journey and enhancing overall logistics transparency.

The firmware also supports time synchronization through GNSS, ensuring that all recorded data are accurately timestamped. This is critical for maintaining a consistent timeline of events, enabling better coordination and data integrity across various operational processes.

Finally, the firmware is equipped with the capability to send collected data to the OneM2M ICON cloud platform. This transmission can be performed directly or through a network of mesh nodes acting as relays or gateways, ensuring reliable data delivery even in complex network environments. This connectivity ensures seamless integration with broader IoT ecosystems, providing stakeholders with real-time insights and enabling efficient remote management of cargo.

Figure 6 shows the architecture of the electronic board; a 3D CAD view is shown in Figure 7.

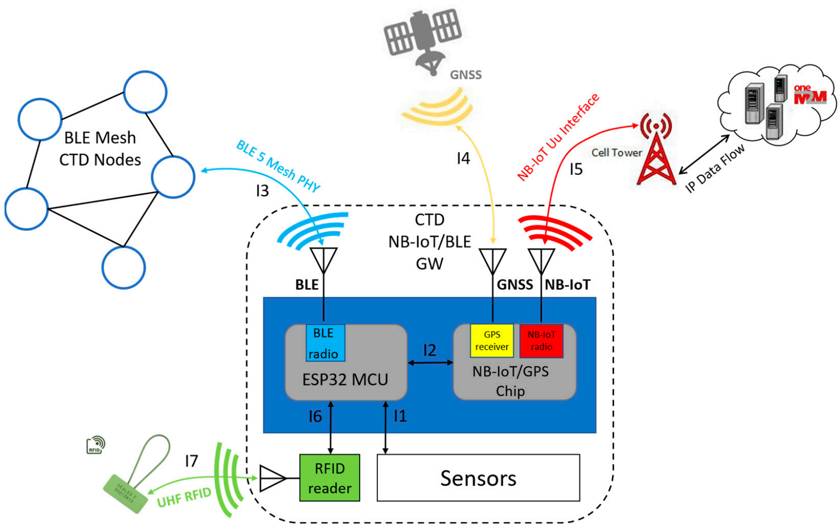


Figure 6. Architecture of the container tracking device.

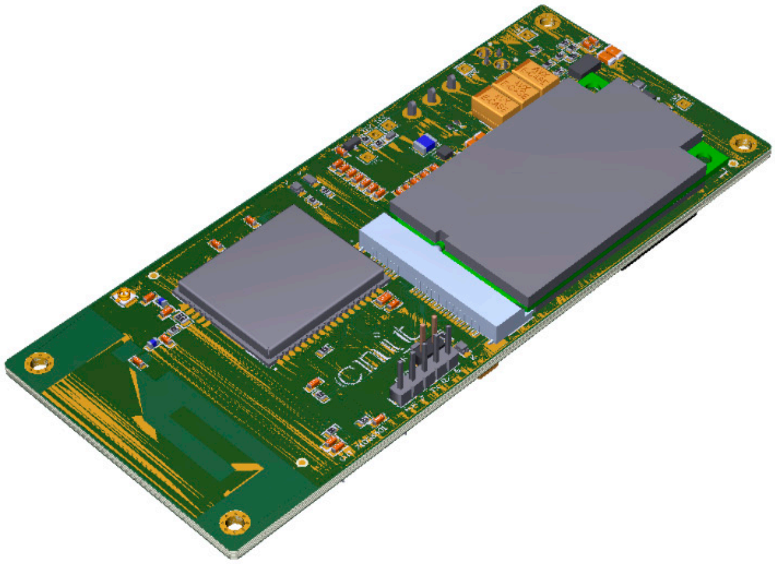


Figure 7. 3D CAD model of the CTD's board.

Figure 8 shows the container provided with the CTD; the photograph was taken during the loading operation on the ship of the field trial.

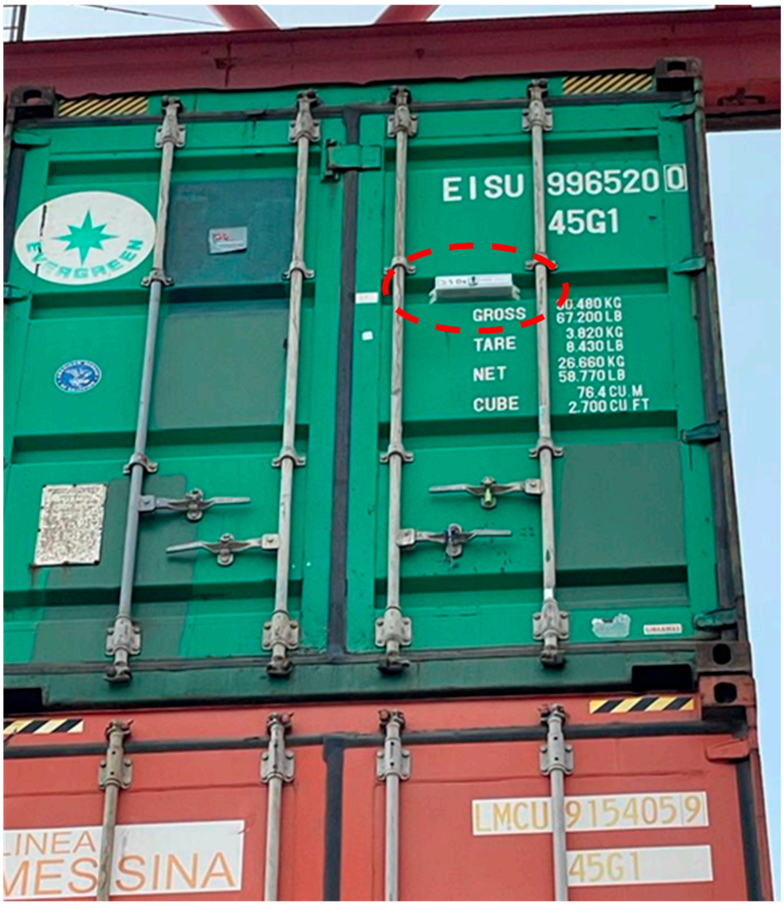


Figure 8. CTD in the red dashed oval placed on the container.

3.4. Onboard Cellular Network

The onboard cellular network was implemented by the evolved Azcom Small Cell platform [32], consisting of an integrated system (the Smart Cell in Figure 4). At the heart of this setup is the Base Band Unit (BBU), which incorporates a System on a Chip (SoC) responsible for managing the entire LTE/NB-IoT protocol stack, in accordance with the standards defined in 3GPP Release 13. This integration allows the system to handle complex processing tasks, such as signal modulation, resource allocation, and error correction, ensuring smooth and efficient data transmission across the network.

Complementing the BBU is the Analog Front End (AFE), which is responsible for generating the RF (Radio Frequency) signal within the designated LTE frequency band optimized for NB-IoT communication. The AFE ensures that the analog signals are transmitted with the necessary clarity and strength, enabling reliable connectivity in diverse environments, including remote or congested areas. The RF module was developed to operate in the 700 mHZ band (B28), to maximize onboard radio coverage, with an in-band carrier and external antenna.

Powering the entire system is the Power Supply Module (PSM), designed to provide stable and continuous energy to all components. This module is crucial for maintaining uninterrupted network operations, particularly in scenarios where consistent power delivery is critical for maintaining communication links.

Finally, the architecture includes a computation unit dedicated to executing the Evolved Packet Core (EPC) functions. The EPC is a central part of the network, managing core tasks such as user authentication, data routing, and connection management. This ensures seamless integration between the radio access network and external networks, facilitating efficient data flow and maintaining overall network stability. This proprietary EPC, compliant with the 3GPP R13 standard, includes the following entities and related interfaces configured as Network In a Box [33]:

- Mobility Management Entity (called V-MME)
- Serving Gateway (called S-GW lite)
- PDN (Packet Data Network) Gateway (called P-GW lite)
- Local Home Subscriber Server (HSS)

Together, these components form a cohesive system that supports advanced LTE and NB-IoT communication, providing robust connectivity solutions essential for modern IoT applications and services.

The system was designed to be suitable with environmental protection class IP67 for the outdoor environment, like onboard the ship.

3.5. The Smart mIoT Gateway

The Smart mIoT Gateway provides secure and reliable multi-backhauling connectivity for ship-shore massive NB-IoT data in all navigation scenarios. At the core of the system is the Smart Switching function, which intelligently routes massive IoT data based on a configurable switching policy. This policy takes into account factors, such as connectivity availability, priority among available links, link costs, and geographic position. Depending on these parameters, the Smart Switching function dynamically selects the most appropriate backhauling link, whether it be a terrestrial or satellite channel. This ensures optimal data routing, improving network efficiency and reducing operational costs.

Complementing this is the Local Resource Status Monitoring function, which continuously tracks the status of local equipment, network infrastructure, and computational resources. By providing real-time insights into resource usage and performance, this function helps maintain network stability and ensures that potential issues are identified and addressed promptly.

To safeguard the onboard network, the Security Gateway function plays a critical role by providing robust network security and data protection. This function is also equipped with threat intelligence capabilities, enabling it to detect and respond to potential security threats, thereby enhancing the overall resilience of the system against cyberattacks.

Finally, the Data-driven Event Management function allows onboard applications to effectively manage and notify of relevant events, such as alerts or alarms. This capability ensures that critical information is promptly communicated to the appropriate stakeholders, both on the ship and onshore, facilitating rapid response to emergencies or system anomalies.

3.6. The 5G-Specialized Satellite Platform

This is constituted by the onboard 5G-specialized Satellite Terminal (5ST), a transceiver guaranteeing connectivity in the open sea via a Ku-band GEO satellite link, and on the ground side by the 5G-specialized Satellite Gateway (5SG). The former includes the IP optimizer software module, which implements the optimization algorithm (including compression and aggregation). The latter performs demodulation and Layer-2 functionalities. Furthermore, for the 5SG component, some virtualized network functions (i.e., routing) were deployed as software modules running on commercial servers in the cloud. This introduced the flexible, dynamic and programmable 5G network paradigm in the 5GT System. Moreover, SDN was deployed in the satellite teleport network to steer the traffic through SDN switches. In this way, the massive data flow data at the passage of the ship from near sea to open sea scenario can be efficiently handled, and the real-time requirements, when the handover between the maritime and the terrestrial domains occurs, are met.

3.7. The IoT Monitoring Platform

The IoT monitoring platform is composed of two main blocks: the ICON OneM2M-compliant platform by TIM [34] and the application platform by Sistematica called "Maritime mIoT Service Framework" (MSF).

The former is a «store & share» platform, implementing resource-oriented RESTful APIs compliant with the OneM2M standard. It is installed by TIM in a data center HW/SW environment to ensure 24 h availability in field trials and research projects.

The latter enables the 5GT services for maritime transport operators, decoupling user services from the underlying OneM2M platform and providing user-defined service with a unique and straightforward interface, aggregating data from other sources. For example, in addition to container data taken from ICON, the MSF applications also aggregate ship location data from the Smart mIoT Gateway GNSS and weather data from external services. An instance of the MSF is installed both in the cloud for users on the ground and in the Smart mIoT Gateway onboard to offer services to the crew as well. The data feeding the onboard applications are constantly updated against the platform for ground users via a OneM2M standard-compliant MQTT broker. Services for users are presented by a web app upon authenticated access by the identity manager. An example of the app access page is shown in Figure 9. The "Ship Monitoring" screen section shows the owner's ship on the map. For each ship, the associated information is shown: ship name, IMO, location and relative age. In addition, a list of the embarked containers is displayed using the button "Show Containers":

- The "Vessel management" function allows for adding new ships to the 5GT system for the registered shipowner, vessels to be deleted, and containers to be loaded and unloaded for each shipload.
- Selecting the "Alarm List" button or the "Alarms" button, the list of alarms is displayed. Each alarm has the following parameters: the ship, the container ID, the alarmed sensor, a description and a flag for the deleted alarm.
- The "Statistics" tab allows two graphs to be displayed: a doughnut with the amount of containers without alarms in green and with alarms in red, and another one that specifies the type of alarm using different colors (e.g., yellow for open door, blue for mechanical bump, etc.).

Figure 9. Web app for the users of the Maritime mIoT Service Framework.

3.8. Operating Scenarios

According to the containers or cargo ship position, the 5GT System operates in four scenarios. For each scenario, the data produced by the container tracking devices (CTDs) are published on the OneM2M IoT platform. Under the assumption that the cargo ship is moving from the near sea to the open sea, all steps reported in Table 1 are presented in Figure 10.

Table 1. 5GT System use case scenarios.

5GT Use Case Scenario	Description
1—Containers are stored in the port terminal.	The CTDs attach the NB-IoT terrestrial cell. The Telco terrestrial domain authenticates them. Thus: 1a—The CTDs send the data to the NB-IoT terrestrial cell; 1b—The terrestrial cell routes the data to the Telco terrestrial domain; 1c—Finally the data are routed to the OneM2M IoT platform.
2—The cargo ship is in "near sea", i.e., the part of the sea where the maritime Telco is not yet authorized to turn on its equipment.	The CTDs are still connected to the NB-IoT terrestrial cell. Thus: 2a—From the cargo ship the CTDs send the data to the terrestrial cell; 2b—The terrestrial cell routes the data to the Telco terrestrial domain; 2c—Finally the data are routed to the OneM2M IoT platform.
3—The cargo ship is in "open sea" (i.e., the part of the sea where the maritime Telco is authorized to turn on its equipment), under the coverage of a WWAN network.	The maritime Telco turns on its equipment. Thus, the CTDs de-tach the terrestrial cell and attach the NB-IoT onboard cell. The Telco terrestrial domain, reached by means of a WWAN network, authenticates them. Thus: 3a—The CTDs send the data to the NB-IoT on-board cell; 3b, 3c, 3d and 3e—From the on-board cell the data are routed to the Telco terrestrial domain by means of the Smart maritime IoT (mIoT) Gateway and the WWAN network; 3f—Finally the data are routed to the OneM2M IoT platform.
4—The cargo ship is in open sea only under the coverage of the satellite network.	The CTDs continue to be connected to the NB-IoT onboard cell. Thus: 4a—The CTDs send the data to the on-board cell; 4b—The on-board cell routes the data to the Smart mIoT Gateway; 4c, 4d, 4e, 4f and 4g—The data are routed to the Telco terrestrial domain by means of the 5G-specialized Satellite Terminal, the satellite link and the 5G-specialized Satellite Gateway; 4h—Finally the data are routed to the OneM2M IoT platform.

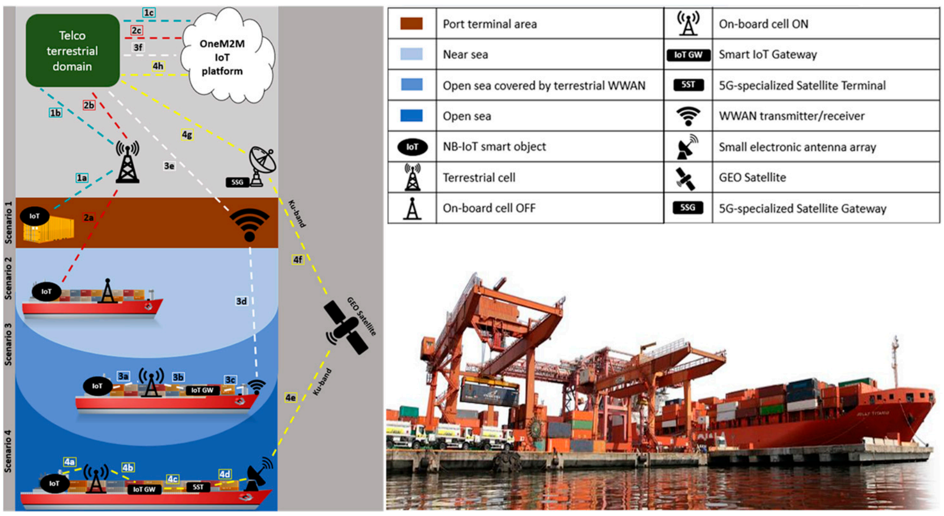


Figure 10. 5GT System scenarios.

3.9. Field Trial

Before the field trial tests, an end-to-end testbed in a laboratory was implemented to verify the interoperability of all the sub-systems composing the 5GT System and assess their performance [35]. Then, the field trial deployment of the 5GT System took place in Genoa at the Intermodal Maritime Terminal (IMT) of the Ignazio Messina & C. cargo ship company on the 12th and 13th of April 2023. The event was run by a team of technicians representing all the partners of the consortium and by ESA technical officers as well. The activities were supervised by Ignazio Messina & C. officers and crew.

It is important to emphasize that the whole hardware system, although prototypical, was made in compliance with stringent requirements for resistance to the marine environment. In particular, the CTD devices on the containers had undergone IP67 pre-compliance testing with immersion for 48 h at the bottom of a one-meter water column.

The field trial validation tests involved the IMT for the terrestrial scenario (see Figure 11) and the Jolly Titanio cargo ship (see Figure 12) travelling from Genova to Mombasa for the maritime scenario.

Figure 11. Deploying of the CTDs on the containers in the maritime yard.

Figure 12. Jolly Titanio cargo ship hosting the field trial tests (source: Ignazio Messina & C.).

The diagram in Figure 13 shows the physical elements of the deployed network onboard and their locations.

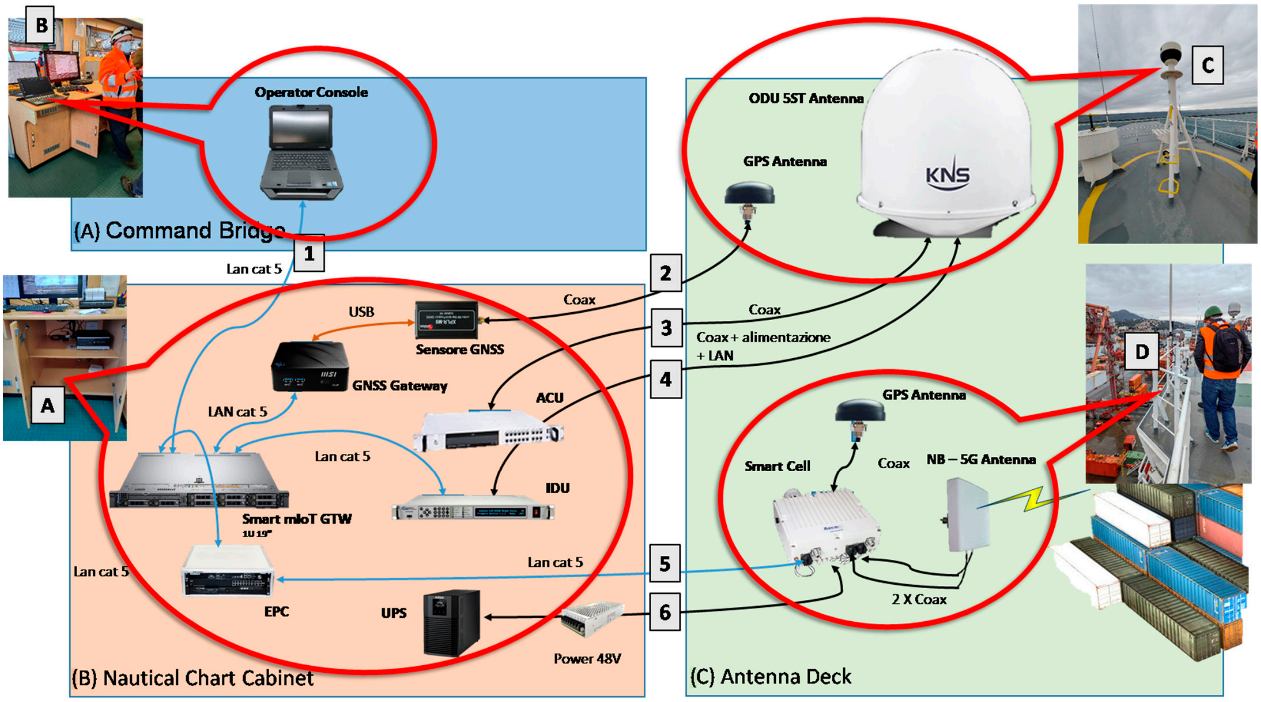


Figure 13. Network elements of the 5GT System installed on board.

Figures 14 and 15 show the external telecommunication equipment of the 5GT System. Figure 16 shows 2 of the 10 CTD-equipped containers being loaded onto the ship. The localization of the rows of containers equipped with CTDs on the travelling ship is shown in Figure 17. A diagram showing the displacement of the stacked containers with the CTD is drawn in Figure 18.

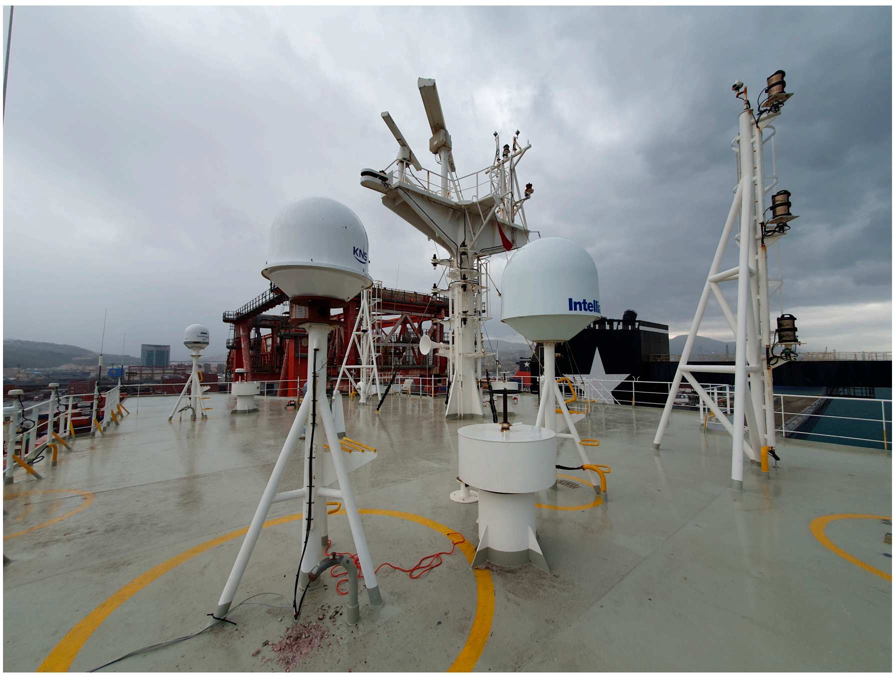


Figure 14. Satellite terminal installed onboard (KNS antenna).

Figure 15. Cellular base station installed onboard.

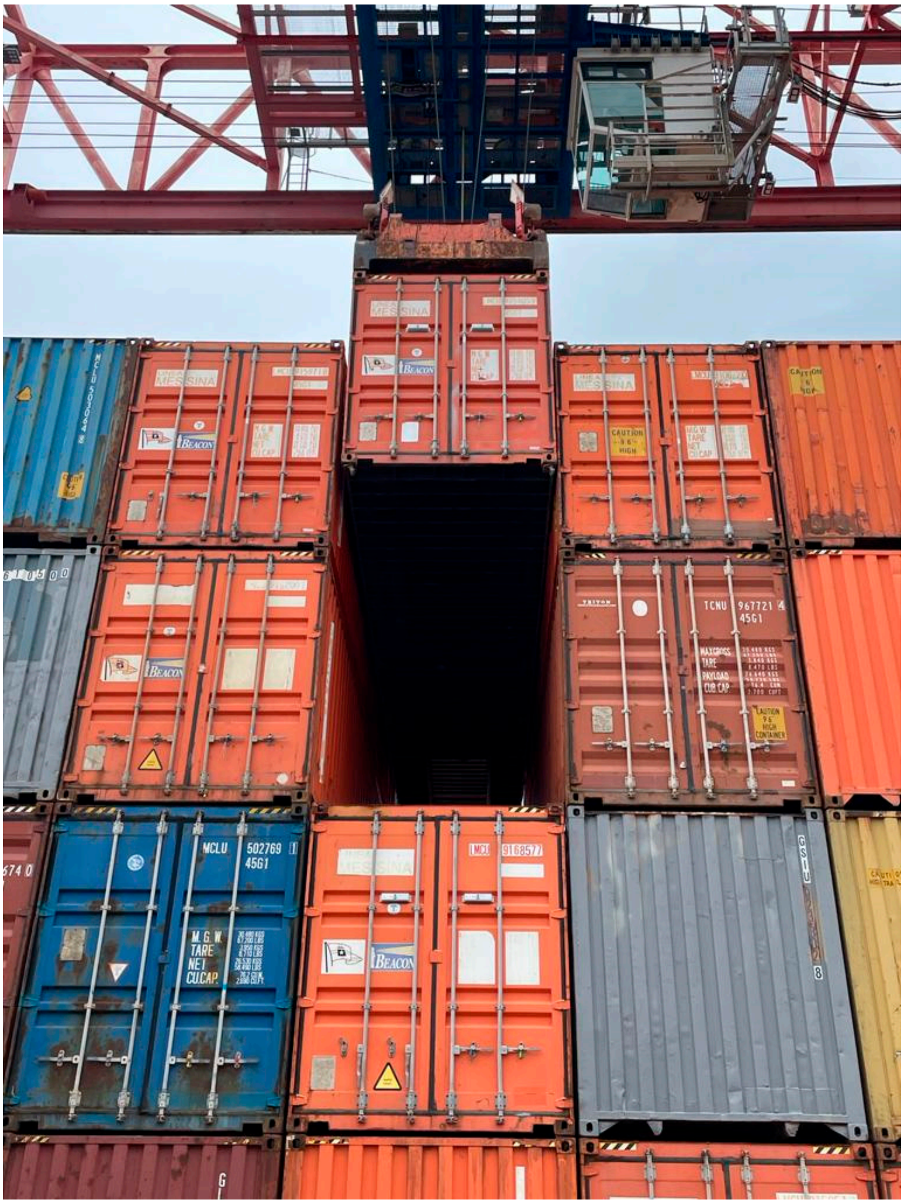


Figure 16. Containers with CTDs loading on the deck of Jolly Titanio ship.

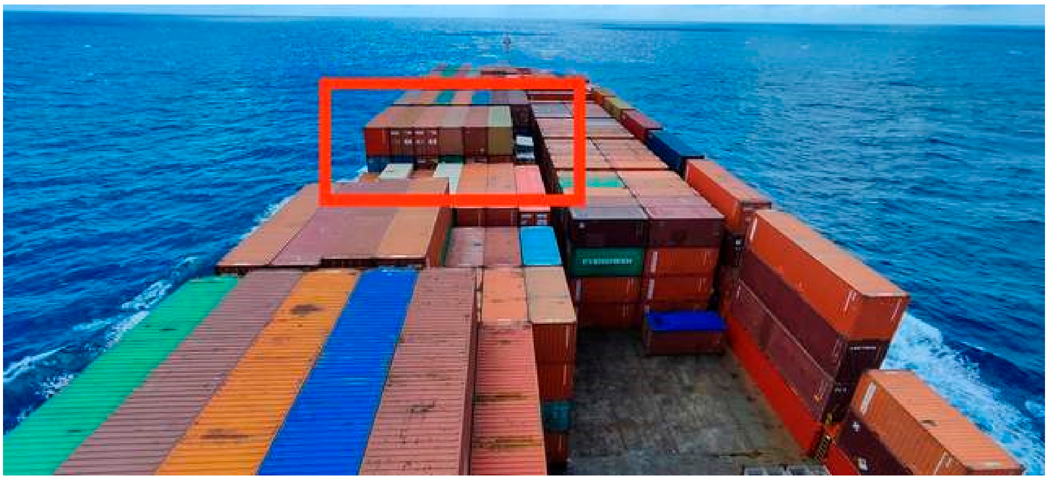


Figure 17. Location of containers with CTDs (in the red box) as seen from the bridge deck.

Figure 18. Diagram showing the placement of CTDs on the ship. The containers at the top (fifth pull) are without CTD because they will have to be unloaded before the final destination of the trip (Mombasa). CTDs are placed on the lower containers at the numbered boxes in the matrix drawn on the photograph.

The equipped containers were only those that would be disembarked in Mombasa, since only in the port of Mombasa are the Jolly Titanio seafarers allowed to disembark from the ship and operate in the yard to retrieve the CTDs. Respecting this constraint, 10 containers (8 of 40 feet and 2 of 20 feet) were equipped; on each of those containers, a pair of CTDs was installed, one with TIM SIM and one twin with AZCOM SIM. The data of each pair are published on the same "content instance" of the TIM ICON platform. To explain this system, let us refer, as an example, to Figure 19, which shows the container with the pair of CTDs "1 Sx" and "1 Dx", and the ICON endpoint for both is the same (i.e., /onem2m/sensor_sea/393315537896/inbox):

Figure 19. Pair of CTDs "1 Sx" (Red) and "1 Dx" (Red) on the container in the yard.

- In the Terrestrial and Near-Sea scenario, the CTD "1 Sx" will send data via a commercial TIM NB-IoT network to/onem2m/sensor_sea/393315537896/inbox, while no NB-IoT data arrive from the CTD "1 Dx" because the Azcom cell on the ship is turned off.
- In the Open Sea scenario, the CTD "1 Dx" will send data via the onboard NB-IoT network to/onem2m/sensor_sea/393315537896/inbox, while no data arrive from the CTD "1 Sx" because the ship's location is not covered by land-based TIM cells.

It must be emphasized that, since the 5G band for NB-IoT B28 (700 MHz) is not yet authorized for mobile communication services onboard vessels (MCV services) [36], to perform the field trial, a specific temporary authorization was requested and granted by the Ministry of Enterprises and made in Italy by the Italian Government. According to this, the field trial was authorized to use the B28 in national waters and open sea (beyond 41 miles from the coast).

4. Results

The field trial tests started in Genoa (Italy) on the 13th of April and ended on the 20th of April when the Jolly Titanio docked at Alexandria (Egypt) seaport. The data produced by the CTDs are related to two main scenarios, the terrestrial scenario and the maritime scenario. Each one, in turn, is divided into the following operational periods:

- Terrestrial scenario
    - ○ Containers in the yard

    - Container loading operations on the ship
    - Containers on the ship at the dock
- Maritime scenario
    - Navigation in "near sea"
    - Navigation in "open sea"

The Jolly Titanio cargo ship left the port of Genoa on 16 April at 4:00 pm, starting the field trial maritime scenario.

During the navigation, the Smart Cell emission on B28 was enabled or disabled in compliance with regulations and authorization in force:

- The cellular base station was turned on beyond 12 miles from the Italian coast;
- The cellular base station was turned off within 41 miles of the foreign coast;

In order to trigger the Smart mIoT Gateway lock/unlock commands towards the base station according to the constraints, a set of geographical polygons were identified over the seas crossed by the Jolly Titanio route (i.e., Mediterranean Sea and Red Sea) up to the satellite Eutelsat 33E coverage limit. Figure 20 shows the geographical polygons identified across the Mediterranean Sea crossed by the Jolly Titanio route. The boundary lines of the white polygons identify a distance of 12 miles from the Italian coast and a distance of 41 miles from the foreign coast.

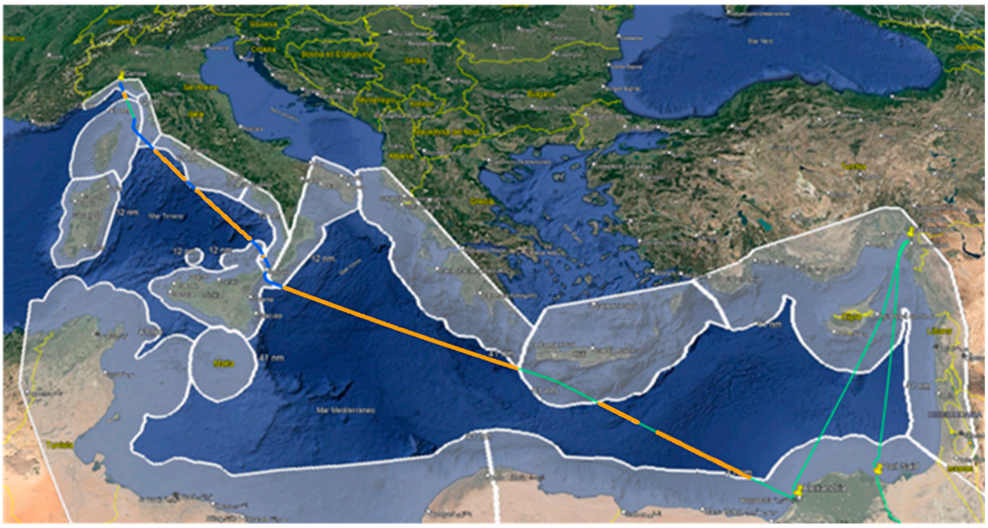


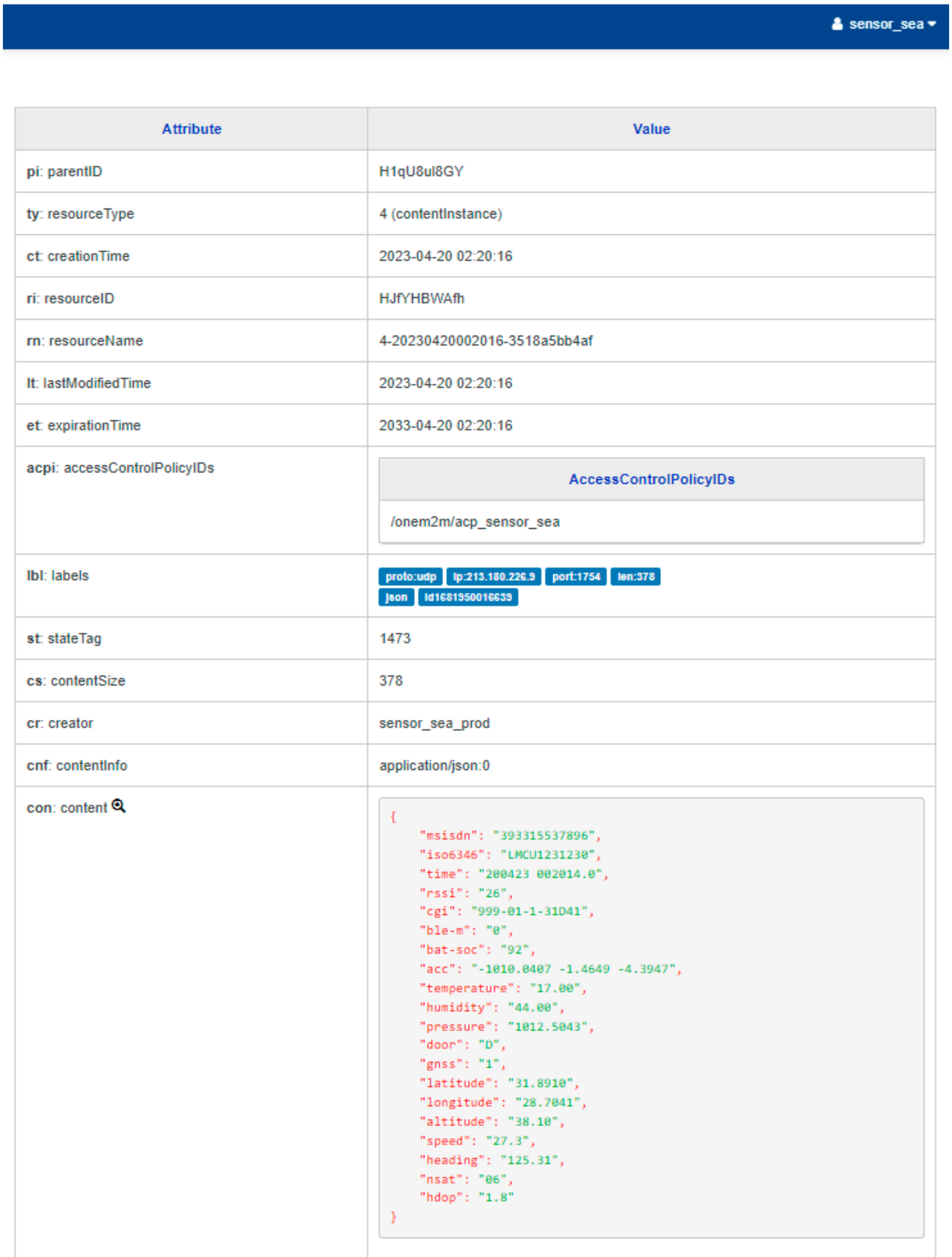
Figure 20. Jolly Titanio route: "near sea" data in blue, "open sea" data in orange, no data in green.

According to the color of the line representing the route followed by the Jolly Titanio, during the field trial, three situations occurred:

1. Blue line → Near-Sea Scenario: the position of the Jolly Titanio was within 12 miles of the Italian coast, and the CTD messages are supported by the TIM terrestrial commercial network.
2. Orange line → Open-Sea Scenario: the position of the Jolly Titanio was beyond 12 miles from the Italian coast and, at the same time, beyond 41 miles from the foreign coast. The CTD messages are supported by the hybrid cellular/satellite network communicating with the onboard Smart Cell.
3. Green line: → The position of the Jolly Titanio was beyond 12 miles from the Italian coast and, at the same time, within 41 miles from the foreign coast (Corsica), the onboard cellular network is off, and no CTD message is transmitted.

For every scenario (terrestrial, near-sea navigation and open-sea navigation), the CTDs produced data showing the status of sensors, radio connections, alarm events, time and positions, battery charge, etc. Those data were directly published to the ICON OneM2M platform, which was also devoted to the storage of all the information from the CTDs during the whole period of experimentation.

The CTDs produced two kinds of messages, synchronous and asynchronous. According to the synchronous transmission operation, each CTD tried to send a message every 30 min via either the NB-IoT network or (if NB-IoT is unavailable) BLE Mesh. The synchronous message contains the updated status of all the monitored values of the containers. On the other hand, the asynchronous message is triggered by an event, which causes the guard thresholds of the temperature, acceleration, pressure, etc., sensors to be exceeded. It is, therefore, an occasional message that contains only event information and an indicator of either alarm onset (when thresholds are exceeded) or alarm cease (when sensors are within thresholds). As an example, a synchronous message sent from a CTD to ICON is shown in Figure 21.



Attribute	Value
pi: parentID	H1qU8ul8GY
ty: resourceType	4 (contentInstance)
ct: creationTime	2023-04-20 02:20:16
ri: resourceID	HJfYHBWAfh
rn: resourceName	4-20230420002016-3518a5bb4af
lt: lastModifiedTime	2023-04-20 02:20:16
et: expirationTime	2033-04-20 02:20:16
acpi: accessControlPolicyIDs	AccessControlPolicyIDs: /onem2m/acp_sensor_sea
lbl: labels	proto:udp ip:213.180.226.9 port:1754 len:378 json id1681950016639
st: stateTag	1473
cs: contentSize	378
cr: creator	sensor_sea_prod
cnf: contentInfo	application/json:0
con: content	{ "msisdn": "393315537896", "iso6346": "LMCU1231230", "time": "200423 002014.0", "rssi": "26", "cgi": "999-01-1-31D41", "ble-m": "0", "bat-soc": "92", "acc": "-1010.0407 -1.4649 -4.3947", "temperature": "17.00", "humidity": "44.00", "pressure": "1012.5043", "door": "D", "gnss": "1", "latitude": "31.8910", "longitude": "28.7041", "altitude": "38.10", "speed": "27.3", "heading": "125.31", "nsat": "06", "hdop": "1.8" }

Figure 21. Synchronous message from a CTD to the ICON platform.

The total message count handled by the MSF since the ship began sailing is shown in Table 2. During the voyage, the periodic messages (TIM-222) transmitted by the CTDs with TIM SIMs are those received from the shore cells when the ship moved away from the port and when it skirted the Italian islands and peninsula within 12 miles. In contrast, the periodic messages transmitted by the CTDs with AZCOM SIM (AZCOM-999) are those transmitted by the shipboard network during the stretches when the radio base station could remain on. In particular, it can be observed that container 4B has never transmitted directly on the TIM terrestrial network, since the device with TIM SIM stopped working immediately, due to a malfunction. Container 1B has never transmitted directly on the AZCOM onboard network, since the device with AZCOM SIM did not work from the beginning. Overall messages transmitted via the BLE mesh network are a considerable number (from 15% to 85% of the total per container). Some asynchronous messages were also transmitted during navigation, mainly driven by the accelerometer for wave movements.

Table 2. Kinds of messages received from the MSF in navigation.

Messages \ Container	5R	4R	3R	2R	1R	5B	4B	3B	2B	1B
TIM-222	23	125	76	16	OFF	NP	OFF	7	15	18
AZCOM-999	108	93	96	99	31	101	81	102	77	NP
Bluetooth mesh	112	130	117	105	150	21	140	27	34	100
Asynchronous	8	16	54	8	8	28	12	12	11	0
Total	251	364	343	228	189	150	233	148	137	118

A more in-depth analysis was conducted on the periodic messages published on the ICON platform. In fact, the payload of the synchronous messages contains not only the sensor values but also the timestamp of sending from the CTD and the value of the cellular signal strength detected by the modem in terms of the Received Signal Strength Indication (RSSI) [37]. Using these data, the following performance indicators were calculated for each scenario:

- delay (s): arithmetic mean of the difference between receiving timestamp on ICON (“ts”) and sending timestamp from CTD (“time”).
- PL (packet loss): % of synchronous messages sent from CTD but not received from ICON.
- RSSI (arbitrary units from 0 (−113 dBm or less) to 31 (−51 dBm or greater)): arithmetic mean of RSSI values for NB-IoT synchronous messages.

The results are shown in Table 3. In the terrestrial and near-sea scenarios, the active cellular network is the TIM commercial network, while in the open-sea scenario, the active cellular network is the onboard AZCOM network with satellite backhauling. Thus, in the first case (terrestrial and near sea), CTDs with TIM SIMs transmit either in NB-IoT mode or in BLE M mode, while CTDs with AZCOM SIMs transmit only in BLE M mode. In the second case (open sea), conversely, CTDs with AZCOM SIMs transmit either in NB-IoT mode or in BLE M mode, while CTDs with TIM SIMs transmit only in BLE M mode. It should be pointed out that two CTDs with TIM SIMs transmitted messages only via BLE M, even when the commercial network was available; these are 1R and 4B. This is because the SIM provider recklessly deactivated them just close to the field trial. In addition, CTD 3B with TIM SIM turned off itself at the beginning of open-sea navigation. Finally, CTD 1B with AZCOM SIM did not work at all.

Table 3. 5GT System performance indicators.

CTD	SIM	Network	Maritime Yard Delay (s)	PL	rssi	# async msgs	Ship at Dock Delay (s)	PL	rssi	# async msgs	Near Sea Travel Delay (s)	PL	rssi	# async msgs	Open Sea Travel Delay (s)	PL	rssi	# async msgs
5R	SIM TIM	NB-IoT	**6.0**	**9%**	**27**	**18**	**4.0**	**6%**	**32**	**55**	**5.0**	**26%**	**20**	**0**	-	19%	-	-
		BLE M	**6.0**		-	-	**na**		-	-	**na**		-	-	7.0		-	-
	SIM AZCOM	NB-IoT	-	21%	-	-	-	12%	-	-	-	28%	-	-	**3.0**	**4%**	**27**	**8**
		BLE M	6.0		-	-	9.0		-	-	13.0		-	-	**na**		-	-
4R	SIM TIM	NB-IoT	**4.0**	**5%**	**30**	**7**	**4.0**	**4%**	**33**	**22**	**4.0**	**27%**	**20**	**0**	-	14%	-	-
		BLE M	**4.0**		-	-	**35.0**		-	-	**9.0**		-	-	7.0		-	-
	SIM AZCOM	NB-IoT	-	22%	-	-	-	60%	-	-	-	12%	-	-	**5.0**	**10%**	**31**	**16**
		BLE M	7.0		-	-	12.0		-	-	4.0		-	-	**4.0**		-	-
3R	SIM TIM	NB-IoT	**4.0**	**9%**	**30**	**8**	**3.0**	**6%**	**30**	**46**	**7.0**	**27%**	**23**	**0**	-	10%	-	-
		BLE M	**na**		-	-	**na**		-	-	**4.0**		-	-	5.0		-	-
	SIM AZCOM	NB-IoT	-	74%	-	-	-	28%	-	-	-	23%	-	-	**4.0**	**8%**	**24**	**54**
		BLE M	13.0		-	-	6.0		-	-	6.00		-	-	**5.0**		-	-
2R	SIM TIM	NB-IoT	**8.0**	**24%**	**31**	**7**	**8.0**	**3%**	**29**	**16**	**2.0**	**34%**	**22**	**0**	-	40%	-	-
		BLE M	**13.0**		-	-	**19.0**		-	-	**4.0**		-	-	na		-	-
	SIM AZCOM	NB-IoT	-	48%	-	-	-	67%	-	-	-	9%	-	-	**3.0**	**9%**	**29**	**8**
		BLE M	8.0		-	-	7.0		-	-	4.0		-	-	**5.0**		-	-
1R	SIM TIM	NB-IoT	OFF	51%	OFF	OFF	OFF	30%	OFF	OFF	OFF	55%	OFF	OFF	OFF	2%	OFF	OFF
		BLE M	10.0		-	-	13.0		-	-	5.0		-	-	3.0		-	-
	SIM AZCOM	NB-IoT	-	54%	-	-	-	46%	-	-	-	31%	-	-	**3.0**	**4%**	**31**	**8**
		BLE M	7.0		-	-	5.00		-	-	5.0		-	-	**3.0**		-	-
5B	SIM TIM	NB-IoT	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
		BLE M	NP		NP	NP	NP		NP	NP	NP		NP	NP	NP		NP	NP
	SIM AZCOM	NB-IoT	-	43%	-	-	-	80%	-	-	-	39%	-	-	**3.0**	**5%**	**31**	**28**
		BLE M	6.0		-	-	15.0		-	-	4.0		-	-	**4.0**		-	-
4B	SIM TIM	NB-IoT	OFF	46%	OFF	OFF	OFF	50%	OFF	OFF	OFF	93%	OFF	OFF	OFF	11%	OFF	OFF
		BLE M	11.0		-	-	7.0		-	-	5.0		-	-	5.0		-	-
	SIM AZCOM	NB-IoT	-	46%	-	-	-	50%	-	-	-	47%	-	-	**5.0**	**7%**	**25**	**12**
		BLE M	11.0		-	-	7.0		-	-	7.0		-	-	**5.0**		-	-
3B	SIM TIM	NB-IoT	**9.0**	**55%**	**28**	**0**	**11.0**	**66%**	**28**	**27**	**2.0**	**36%**	**17**	**0**	OFF	OFF	OFF	OFF
		BLE M	**14.0**		-	-	**6.0**		-	-	**na**		-	-	OFF		OFF	OFF
	SIM AZCOM	NB-IoT	-	72%	-	-	-	40%	-	-	-	27%	-	-	**2.0**	**3%**	**29**	**12**
		BLE M	9.0		-	-	8		-	-	4.0		-	-	**10.0**		-	-
2B	SIM TIM	NB-IoT	**7.0**	**38%**	**30**	**1**	**na**	**68%**	**27**	**19**	**12.0**	**53%**	**18**	**0**	-	95%	-	-
		BLE M	**11.0**		-	-	**na**		-	-	**22.0**		-	-	4.0		-	-
	SIM AZCOM	NB-IoT	-	56%	-	-	-	21%	-	-	-	18%	-	-	**8.0**	**22%**	**8**	**11**
		BLE M	8.0		-	-	9.0		-	-	7.0		-	-	**5.0**		-	-

Table 3. *Cont.*

CTD	SIM	Network	Maritime Yard Delay (s)	PL	rssi	# async msgs	Ship at Dock Delay (s)	PL	rssi	# async msgs	Near Sea Travel Delay (s)	PL	rssi	# async msgs	Open Sea Travel Delay (s)	PL	rssi	# async msgs
1B	SIM TIM	NB-IoT	**7.0**	**43%**	**28**	**15**	**6.0**	**31%**	**29**	**62**	**9.0**	**30%**	**17**	**0**	-	9%	-	-
		BLE M	**5.0**		**-**	**-**	**14.0**		**-**	**-**	**6.0**		**-**	**-**	5.0		-	-
	SIM AZCOM	NB-IoT	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
		BLE M	OFF		OFF	OFF	OFF		OFF	OFF	OFF		OFF	OFF	OFF		OFF	OFF

Despite these drawbacks, the field trial overall shows very good results. The comparison between the indicators in Table 3 shows, in general, that CTDs transmit better in the "open sea" scenario than in the "near sea" and terrestrial scenarios. The packet loss values of the 5GT System with satellite backhauling in operation ("open sea") are always lower than the values recorded on commercial cellular networks, while the delay values are equivalent. Moreover, in all scenarios, the performance of the BLE M network in terms of both packet loss and delay is always equivalent to that of the NB-IoT network with even better results in terms of packet loss. The worst-performing scenario is the "near sea" travel. This is in line with expectations since, in this scenario, the sailing ship is reached by the cellular signal from shore cells that are up to 21 miles away. In this scenario, the CTDs record lower RSSI values than the other scenarios due to the distance of the commercial land-side base station from the coastline and, consequently, higher packet loss.

As for asynchronous messages, they were mainly triggered by the accelerometer. It should be noted that more of them were sent during the terrestrial scenario than during the maritime scenario; also, no asynchronous messages were sent during near-sea navigation. This finding is in agreement with the fact that during loading operations, the ship and containers experience the greatest mechanical stresses; furthermore, navigation in open sea has rougher swell than in near sea.

The graphs in Figures 22–25 show latency histograms of some representative containers to evaluate in more detail the differences between the commercial cellular network (land-based and "near sea" scenarios), the hybrid satellite/cellular network ("open sea" scenario) and the contribution of the BLE M network. The diagrams show that although the average latency values (a few seconds) are comparable in all scenarios, in the open sea, some rare messages can reach latencies of up to 120 s. This is probably due to the characteristics of the satellite link.

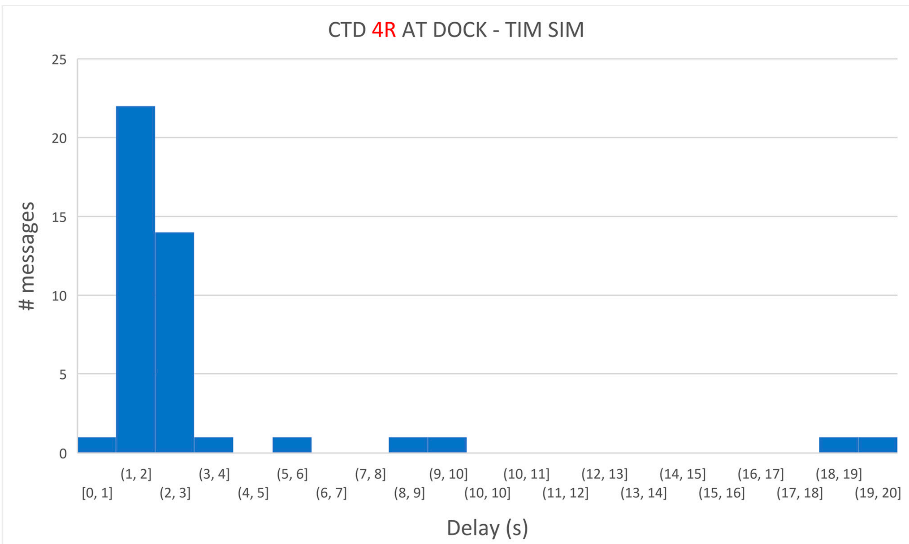


Figure 22. Latency histogram CTD 4R at the dock—TIM SIM.

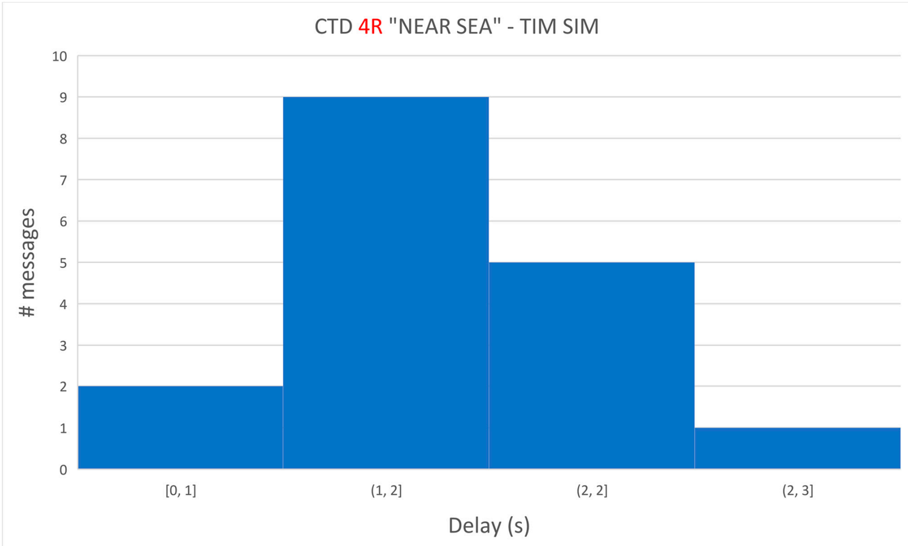


Figure 23. Latency histogram CTD 4R "Near Sea"—TIM SIM.

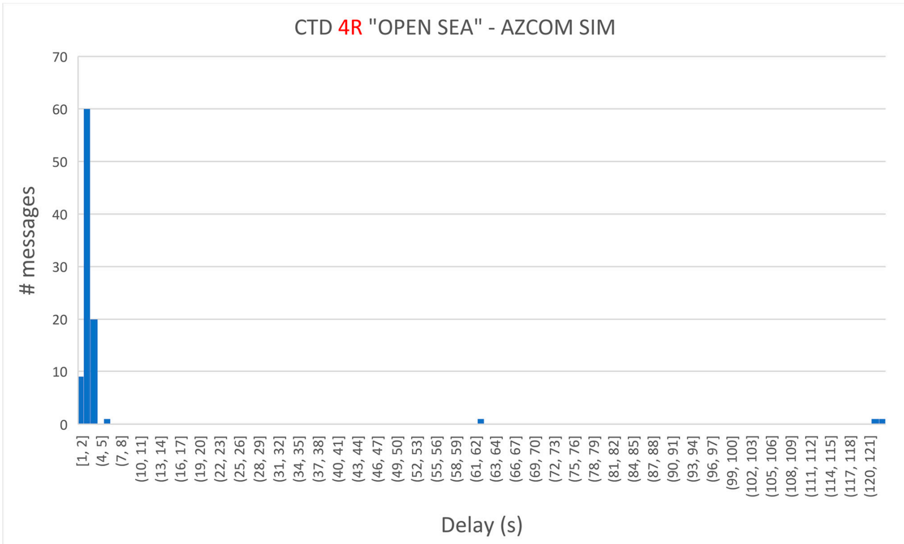


Figure 24. Latency histogram CTD 4R "Open Sea"—AZCOM SIM.

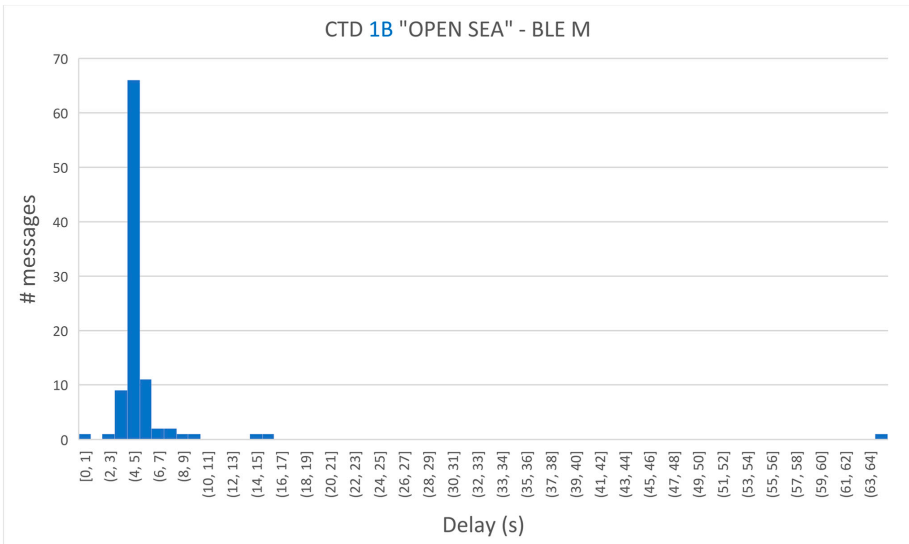


Figure 25. Latency histogram CTD 1B "Open Sea"—BLE Mesh.

In Figures 26–28, the NB-IoT message loss is plotted vs. the max latency values for the three scenarios in which the containers are onboard. In graphs, symbols are measurements and the dashed line is linear regression. We can see that there is a slight linear correlation for the travelling scenarios (near sea and open sea) but no correlation at all when the ship is anchored at the dock.

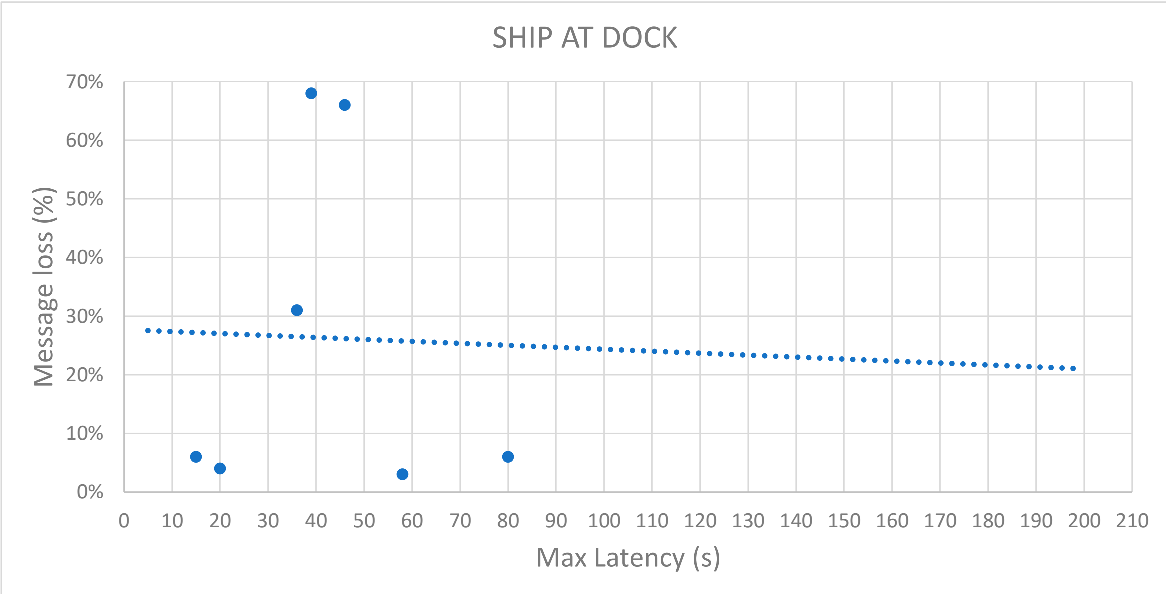


Figure 26. Plot NB-IoT message loss vs. max latency—ship in dock scenario.

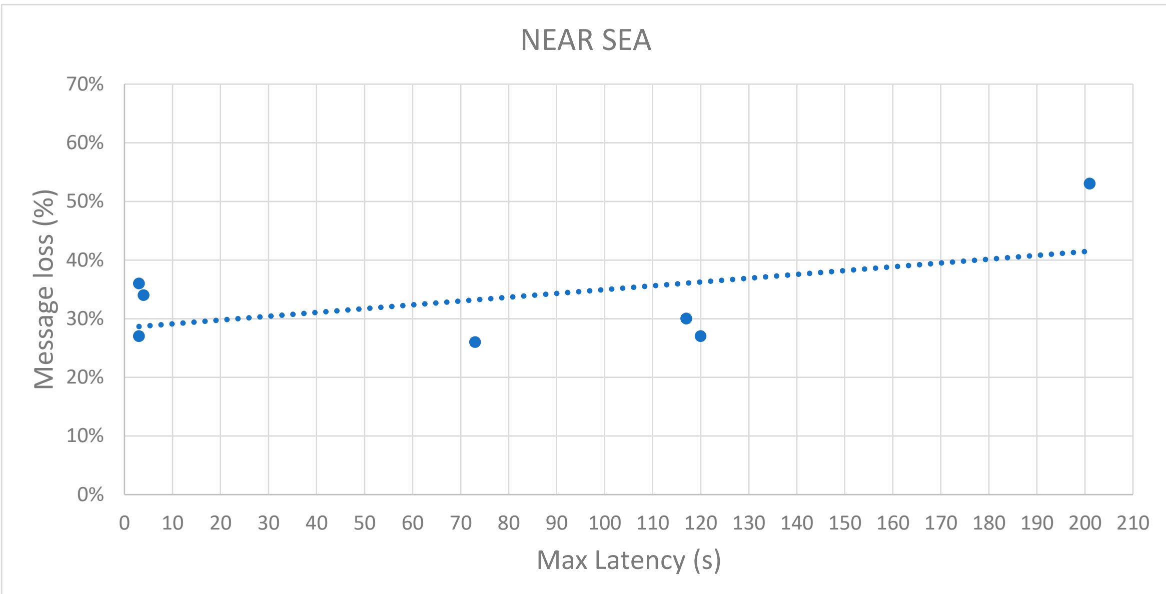


Figure 27. Plot NB-IoT message loss vs. max latency—near-sea scenario.

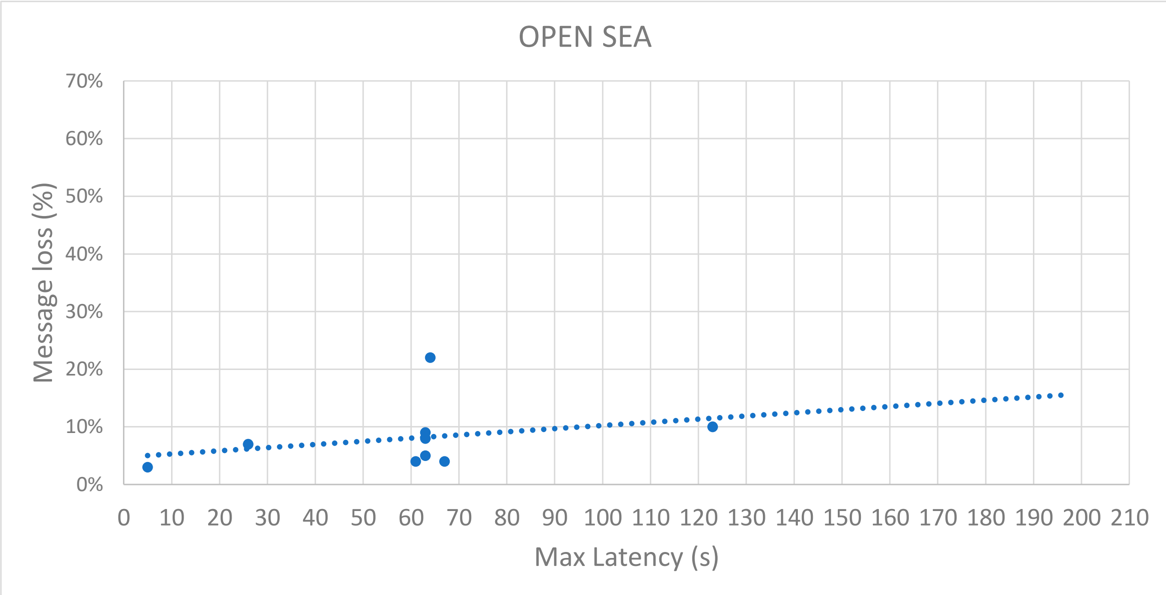


Figure 28. Plot NB-IoT message loss vs. max latency—open-sea scenario.

5. Conclusions

The 5G SENSOR@SEA project realized a low-cost tracking and monitoring system for "general purpose" ISO containers that integrates 5G cellular technologies for massive Internet of Things with a satellite-optimized backhauling link. With the cooperation of four industrial partners and a telecommunication research center, the so-called "5GT System" was designed, developed, tested and validated up to field trials. Several modules of the system were designed, built and finally installed on the ship and in the teleport: the container tracking devices placed on the containers, the NB-IoT cellular network with optimized satellite backhauling, the Ku-band GEO satellite terminals and the maritime service platform based on the OneM2M standard. The field trial conducted during the intercontinental liner voyage of a container ship showed the validity of the project. The 5GT System is still a prototype that, although designed to operate under the challenging conditions of containerized ocean transportation, had never been tested under real operating conditions, before the field trial. The performances of the hybrid cellular/satellite network in the field trial are a world first, and it is also possible to compare them directly with the performances of the commercial cellular network, because "twin" tracking devices have been deployed. The field trial also provided some insights on how to make the system installation and devices more robust, in subsequent developments.

During the whole travel, all the components of the 5GT System worked correctly, including the Maritime Service Framework applications and the management of the lock/unlock switching of the onboard Smart Cell.

The performance indicators (lost messages and latency) show, in general, that CTDs transmit better in the "open sea" scenario than in the "near sea" and terrestrial scenarios. The packet loss values of the 5GT System with satellite backhauling in operation ("open sea") are often lower than the values recorded on commercial cellular networks, while the delay values are equivalent.

The worst-performing scenario is the "near sea" travel, in line with expectations, since, in this scenario, the sailing ship is reached by the cellular signal from shore cells that are up to 21 miles away. In this scenario, the CTDs record lower RSSI values than the other scenarios and, consequently, higher packet loss and higher latencies due to retransmissions by NB-IoT.

The field test also showed a relevant number of lost messages: from 3% up to 22% in "open sea" and even more in the scenarios relying on commercial NB-IoT networks only.

The loss of messages resides in the NB-IoT Link mostly. It could be mitigated by acting in three directions: (i) the optimization of transmission protocols in the core network; (ii) the adoption of a more robust transmission protocol by the CTD, e.g., CoAP (suitable for high-loss connections) instead of raw UDP; (iii) improvements in CTD software introducing retransmission algorithms at the application layer in the case of lost messages.

Regarding cellular transmission bands on the ship, the trial showed that, per current international regulations [36], the B28 band, while favorable in terms of signal propagation on the ship's decks, cannot be used outside territorial waters, between 12 nm and 41 nm. In order to ensure the operation of the 5GT System in this zone as well, it will be necessary to use a permitted band (e.g., B3 band) or propose changes in the regulations to the relevant bodies.

More generally, in this area, important developments are expected to be achieved with the integration of NB-IoT NTN direct communication with GEO and LEO satellite communication technologies and 6G cellular networks for the massive development of the Internet of Things.

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Data Availability Statement: All data can be found within the article.

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