Evaluation of LoRa Technology for Vehicle and Asset Tracking in Smart Harbors

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***Abstract*—Tracking of goods, containers, and vehicles in harbors is a challenging task because seaports typically are in a secluded area with limited networking capability. Existing solutions use the combination of RFID tagging and Wireless Sensor Networks (WSN). A harbor is considered a harsh industrial environment with metallic components and surfaces. These conditions influence the wireless networking performance. In addition, harbors' areas vary from 500 ha to 7500 ha. Hence, the coverage range of wireless systems and the exposition to interference are considered. LoRa (Long Range) technology becomes a promising solution among other Low Power Wide Area Networks (LPWAN). Therefore, we investigate the LoRa technology to locate and track assets in harbors. Through ns-3 simulations on scalability, interval rate, and coverage range performance metrics, we evaluated the feasibility to use LoRa in seaports. In our experiments, we applied 1000 LoRa nodes within a radius of 2500 m to the gateway. The results exhibit a probability of successful transmission of 85% in an interval of 300 sec.**

***Index Terms*—LoRa, LoRaWAN, Localization, Wireless Sensor Networks, LPWAN, Harbor, Industrial Internet of Things.**

I. Introduction

The evolution of Internet of Things (IoT) has turned out to be a promising solution for improving every aspect of daily life. IoT enables an enormous number of different applications to be connected via wireless communication into a big integrated network. Industrial IoT (IIoT) is an IoT approach to improve the industrial automation process and work efficiency by incorporating new technology such as machine learning, big data, and wireless communication. Thus, enabling the industry to make smarter business decisions faster.

Seaports act as the primary business player for supporting the global supply chain system. Port management and transportation of goods are relying from the speed and throughput of the logistics supply chain. Typically, seaports' areas vary from 500 ha to 7500 ha. An enormous number of activities may occur daily within this large area, primarily the loading and unloading processes. Thus, time is a critical parameter in a seaport, where a truck must be available right before the ship arrives. Therefore, delays while deploying the assets to the intended destination are considered.

Applying IoT technologies reveals a potential solution to solve this challenging industrial use-case. Geolocation and tracking emerge as an innovative opportunity to support and resolve such industrial schemes. Localization acquired through global navigation satellite systems (GNSS) improve the position precision of both, the truck and the asset. Nevertheless, the coverage range of wireless communication is recognized as a problem in a harbor use-case. Low power wide area networks (LPWAN) open a favorable solution to overcome the problem. The integration between low data rate and robust modulation allow LoRa to achieve several kilometers of communication range [1].

To the best of the authors' knowledge, this is the first paper that analyze the usage of LoRa for improving yard management in harbors. In this project, we analyze LoRa regarding its capability to transfer data in harbors in a timely manner and evaluate LoRa throughput by means of ns-3 based simulations. The goal is to estimate the potential and limitations of LoRa technology in harsh environment of harbors. The paper is organized as follows. In section two, seaport use-case and the proposed solution will be provided. Section three explains the technical background of LoRa technology. Section four describes the related work for LoRa in industrial applications. Section five explains the implementation of the ns-3 LoRa model. The conducted simulation experiments and results will be summarized in section six. Finally, the conclusion of this paper will be provided in section seven.

II. Asset handling and vehicle coordination in seaport

A Seaport, as one of the gates of logistic operations, acts as the primary business player for supporting the global supply chain system. It represents the bridge between the customer of the country or city, where the port operates. According to [2], around 9,000 movements are carried out daily for a 15,000 TEU (20ft equivalent unit, i.e., cap. of containers) vessel in Busan, South Korea. These figures of high throughput explain the necessity to improve seaport management and transport.

A. Problem description of a typical harbor operation - harbor use-case

A typical harbor consists of quay, yard, truck and train areas (see Figure 1); the yard area is the most important area for a successful logistic turnaround [3]. The three significant means of yard management are yard cranes management, yard vehicles management, and yard spaces managements. Figure 1 demonstrates the blueprint and the components of the harbor operation system. The seaside process encompasses the following steps [4]: When the vessel (the container ship) arrives at the quay, the containers or assets will be taken by

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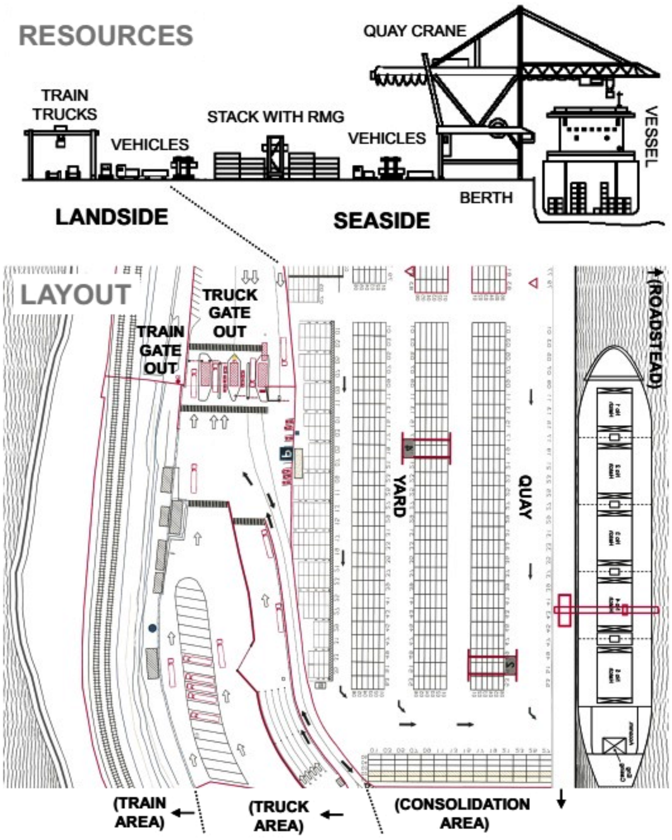

Figure 1. Layout and components of the seaport system [4].

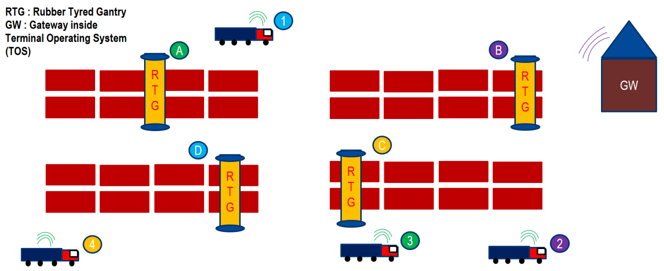

Figure 2. Harbor use-case: truck and asset localization.

the quay crane. First, unloaded containers are delivered to the yard area by a trailer truck or automatic guided vehicles (AGV). Then, containers are arranged into stacks and placed into different areas according to type (export, import, special container). The adjustment of each stack is organized by rubber tired gantry (RTG) or rail mounted gantry (RMG). RTG is a mobile gantry crane, equipped with rubber tires, while RMG are based on rails [4]. Finally, the container can be picked up in the consolidation area by a road truck. All processes are coordinated by the Terminal Operating System (TOS).

Separately on the landside, an external truck must first check in before entering the harbor area. During this process, the driver executes document verification with the gate authorities. If the truck is registered to enter the port area, the TOS authorities guide the drivers to the next step. In this case, two possibilities can occur: Either the truck waits in the parking area until the asset is available or the truck moves to the corresponding location of the container block. If vehicle and asset are not synchronized before the pickup of the asset, several bottleneck situations can occur in the yard. These circumstances lead to delay of asset distribution or shipment. To reduce traffic congestion inside the yard area, the study [5] stated a proper truck sequencing and scheduling need to be implemented for entering the consolidation area. Besides the yard management aspect, the management of vehicle dispatching is also one additional critical key to improve harbor performance. To summarize, localization and tracking technologies are required to assert continuous location of assets and trucks. As a result, synchronization of all seaport activities in real-time can be achieved.

B. Existing solution: Radio-Frequency Identification (RFID) tagging and Wireless Sensor Networks (WSN)

As explained in subsection II-A, the harbor is characterized as a wide area and harsh environment with a multitude of metallic components and surfaces. Typical harbors lack network infrastructures, such as LTE, 5G, Wi-Fi. Common wireless technologies do not provide optimal solutions for harbor application. Hence, it is evident that a harbor has specific requirements to establish an information and communication technology (ICT) infrastructure. The discussed points in this paper reflect on how to extend towards an effective yard management system for asset and vehicle dispatching. In order to resolve these aspects, the research of [4] justified the use of RFID technology and WSN on containers and trucks to achieve real-time synchronization and localization of seaport activities and components. Recently, a new wireless standard called LoRa can be applied as WSN. This technology reveals an affordable network infrastructure with small installation costs to equip a harbor use-case.

C. Proposed solution: transmission of location data by means of LoRa

In this paper, we investigate the LoRa technology to transmit location data of trucks and assets in harbors. Geolocation and tracking capabilities emerge as an innovative opportunity to optimize the seaport business process. The coverage range of wireless communication is often considered a problem in a harbor. LPWAN, especially LoRa, come as a potential solution to overcome this problem due to their high receiver sensitivity capability. The proposed solution is to broadcast the current location data received via GNSS to a central gateway via LoRA. The problem to be solved is how LoRa technology can be used to send the location information in a timely manner. LoRa was developed for low data rates and higher transmission range. LoRA is using CSS modulation and a receiver is able to accept a packet correctly, even though there is another transmission overlapping at the same time. Furthermore, Lora is subject to duty-cycle regulation. This means that the sending nodes may only be active for a certain period of time and that only small data packets can be transmitted. Consequently, we analyzed scalability, interval rate, and coverage range to evaluate the applicability of LoRa technology and to find out optimal configurations for the harbor use-case.

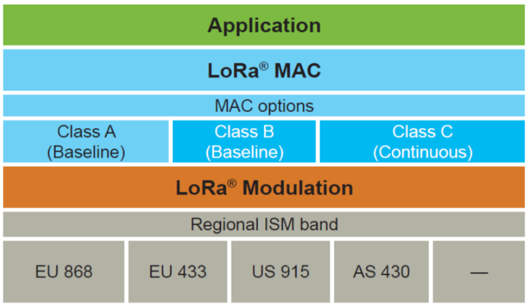

Figure 3. Illustration of the LoRaWAN network architecture [6].

Figure 2 illustrates the suggested solution, which shows the usage of the localization system. The approach aims to achieve efficient and precise decisions for yard management and vehicle dispatching. The trucks in Figure 2 are coordinated by the Terminal Operating System (TOS), that uses the information received from the LoRa gateway. The information is sent by each truck, while moving to the appropriate container block destination (e.g., truck 1 to block D). The mobile LoRa-box, which is given to the truck driver at the check in process, contains a GNSS receiver and a LoRa transceiver. Instead of attaching further LoRa-localization-devices to the container, every RTG in each block is permanently equipped with a LoRa-box. Hence, all LoRa nodes are able to transmit the exact location of the container and truck, assuming a container won't move by itself.

The proposed system enables the port authorities to minimize traffic congestion, enhance the safety of all entities, and improve the yard management in the seaport area.

III. Overview of LoRaWAN and LoRa technology

A. Existing wireless technology solutions

The Low Power Wide Area Network (LPWAN) is often used as a solution to overcome the power consumption problem in other IoT applications. Examples for existing LPWAN solutions in the market are LoRa (Long Range), SigFox, and NB-IoT (Narrow Band). NB-IoT and LoRa allow massive wireless connections to be covered up to extended range at low power consumption. NB-IoT is based on narrow band radio technology and the 3GPP standard. It is a derivation from cellular communication, which works on the existing LTE and GSM networks under the licensed frequency band. According to [7], the licensed channel band cost over 500 million euro per MHz, while the deployment cost per base station is more than 15,000 Euro. In contrast, LoRa technology operates in an unlicensed channel band that varies from region to region. Thus, the spectrum channel is free but must follow duty-cycle regulations that vary between 0.1%, 1% and 10%. Based on the Semtech datasheet [8], it can perform wireless transmission up to 15 kilometers length.

B. LoRaWAN and LoRa technology

Semtech has introduced LoRa products with long transmission range by utilizing chirp spread spectrum technology. LoRa is the physical layer used in LoRaWAN. Meanwhile, LoRaWAN (Long Range Wide Area Network) is a Medium Access Control (MAC) layer protocol. The architecture design is generally arranged as a star topology network [9]. Figure 3 specifies the LoRaWAN stack specification.

1) LoRaWAN technology LoRaWAN operates on LoRa in the unlicensed ISM band of 863-870 MHz in Europe. A LoRaWAN gateway is responsible for passing raw data packets to the network server and vice versa. Inside the network server, security checks and data rate adaptation are applied during decoding [10]. In the end, the data will be forwarded to specific application servers. LoRa network infrastructure implements the Adaptive Data Rate (ADR) algorithm. The data rate and battery life of the individual end devices are managed and optimized. The LoRaWAN MAC layer allows multiple communications with the gateway receiver. The ALOHA communication method enables a transmitter to send packet data, whenever a frame is needed to be transmitted. In a LoRaWAN network, all nodes are asynchronous and based on ALOHA technique. This means each node in a LoRaWAN network may become active in certain time intervals. The nodes are either checking the downlink or synchronizing the messages.

2) LoRa technology LoRa implements Chirp Spread Spectrum (CSS) modulation. Chirp simply means a signal changing its frequency from a minimum to maximum (up-chirp) and vice versa (down-chirp). Forward error correction (FEC) is required during propagation to achieve robustness and increase receiver sensitivity [11]. CSS modulation allows a trade off between the data rate and the transmission range or power. LoRa is able to reach long communication ranges up to 2-5 km in urban areas and 15 km in less dense areas [12]. LoRa transmission works as following, the transmitter generates a chirp signal by varying the frequencies (sinusoidal pulses) over time. Meanwhile, the phase between adjacent symbols is kept constant. The generated signal is resistant to doppler shifts and multipath fading. It is also robust towards interference or signal jamming [11].

a) Spreading Factor (SF) During transmission, each frame will be propagated with a particular Spreading Factor (SF) [11]. LoRa utilizes a SF value between 7 and 12, which can be set during configuration of the LoRa node, also between frames. The spreading code is divided into codes with a length of $2^{SF}/SF$. Each symbol is spread by substituting to multiple chips of information as mentioned in Figure 4 [11]. Hence, the spreading factor directly affects the effective data rate. The trade-off mechanism in CSS allows varying data/bit rate (Rb) ranges from 0.3 kbps to 6.8 kbps, which depend on the SF value. A higher SF number has lower data rate, longer time on air and higher receiver sensitivity than a lower SF number. The correlation is shown in Table III-B2b with the bandwidth parameter at 125 kHz.

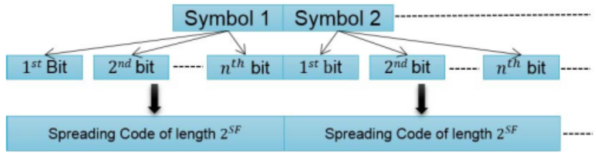

Figure 4. Symbol Spreading in LoRa [11].

Table I
THE RELATIONSHIP BETWEEN SF WITH DATA RATE (RB), SINR, RECEIVER SENSITIVITY, AND TIME ON AIR (TOA) [1], [11], [13], [14].

SF	Rb (Kbps)	SINR (dB)	Rx Sensitivity (dBm)	ToA (ms)
7	6.8	-7.5	-130.0	62.48
8	3.9	-10.0	-132.5	65.95
9	2.2	-12.5	-135.0	79.88
10	1.2	-15.0	-137.5	113.77
11	0.67	-17.5	-140.0	192.55
12	0.37	-20.0	-142.5	340.1

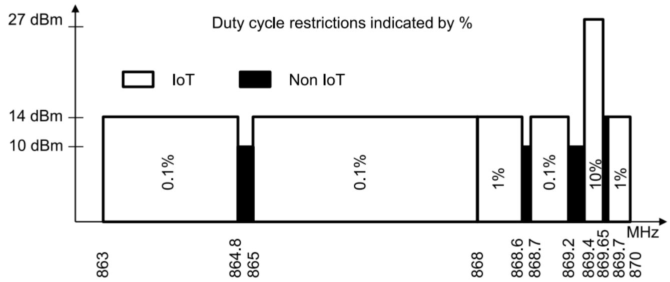

Figure 5. Duty cycle restriction in EU band channel [15].

b) Spreading Factor Orthogonality LoRa can communicate in an orthogonal spectrum under different spreading factor setups, while it uses the same bandwidth and frequency channel band. Magrin and Vangelista [13] explained that a receiver is able to accept a packet with spreading factor i correctly, even though there is another transmission with spreading factor j overlapping at the same time. Since the obtained packet's Signal to Interference plus Noise Ratio (SINR) is higher than a particular threshold (based on SF i and j) and SF $i \neq j$. This means that different LoRa devices may transmit with a different SF value and different sub-channel frequency band. The devices can transmit simultaneously and in parallel as long as the SINR threshold rules are met.

3) LoRa Limitation Due to the usage of LoRaWAN in the unlicensed ISM bands (863-870 MHz), regulations must be obeyed in implementations. Based on European regulations [15] and Figure 5, it should adapt with duty cycle regulation on a per sub-channel band usage. According to [12], the duty-cycle in a sub-band can be represented as d and time on air is denoted as Ta. Because of duty cycle restrictions, a device must be in off-period for the specific duration $Ts = Ta(1/d-1)$. Simultaneous transmission in each device can occur if we use different SF and frequency channel bands. The gateway is also able to decode and receive multiple transmissions from the end device simultaneously because of the orthogonality spectrum of LoRa [16]. Nevertheless, it needs multiple radios to receive parallel transmissions.

IV. RELATED WORK FOR LORA IN INDUSTRIAL APPLICATIONS

This section is set to present the state of the art correlating with LoRa deployment in industrial application.

A. Transmission performance of LoRa nodes

The examination of LoRa nodes in industrial environments [1] was carried out in Naaldwijk, Netherland. The results exhibit that SF 12 gained higher coverage range than SF 7. RSSI (Received Signal Strength Indication) and the SNR (Signal to Noise Ratio) values are varied in different positions of the node. The diverse RSSI values were obtained due to the Line of Sight (LOS) and non-LOS conditions of end devices towards the gateway. Greater distance to the gateway leads to decreasing RSSI values.

Experiments in [17] examined the factors that may influence packet loss during activity of multiple LoRa nodes. LoRa transmission with SF i can survive the interference from another LoRa transmission with SF j, if the difference of SNR between them is sufficient. The results in [13] also declare that interference is only a minor issue, if the SNR is lower than 5 dB above the desired signal for SF 7 and 19.5 dB for SF 12. The authors of [13] present three probabilities of receiving packets in a transmission: probability of correct reception of a weak signal, probability of correct reception of a strong signal, and the probability of losing packets with weak and strong signal strengths. To sum up, if one of two simultaneous packets arrives at the receiver with a higher power or higher SNR than the another one, the packet can be demodulated by the LoRa receiver. Greater SF values provide wider transmission range in an industrial area.

B. Scalability analysis of LoRa network

The growing number of end devices in a LoRa network is a big issue as the limited time on air has to be managed. Thus, scalability analysis is a critical concern before deploying LoRa into an industrial environment. LoRaSim, as introduced in [16], is a simulator to evaluate and study the LoRa scalability. The simulation shows that only up to 120 nodes can be handled in one gateway due to the collisions [16], [18]. F. van den Abeele et al. [19] conducted a LoRaWAN simulation with the network simulator ns-3. The results reveal that, as the number of nodes growing for both confirmed and unconfirmed uplink transmissions in a single gateway, the packet delivery ratio is declining. Unconfirmed transmissions demonstrate a better success rate of packet delivery compared to confirmed transmission because of the overhead of traffic in the network and its collisions.

C. Approach for LoRa deployment in the industrial use-case

LoRaWAN is designed for sporadic communication and not for continuously exchanging data, like other wireless technologies. A centralized management protocol can regulate the behavior of each node and performance of the network by minimizing the coexistence conflicts of the deployed nodes [20]. Time Slotted Channel Hopping (TSCH) is one of the approaches for the centralized protocol. This approach manages many different communication channels with a time slot scheduling approach.

The network server schedules simultaneous communications based on the LoRa spreading factor orthogonality feature. This refers to a communication using diverse number of sub-channel frequencies and spreading factors. Theoretically, LoRa can have up to $N_{SFmax} \times N_{CHmax} = 48$ simultaneous unconfirmed communications [20]. $N_{SFmax} = 6$ is denoted

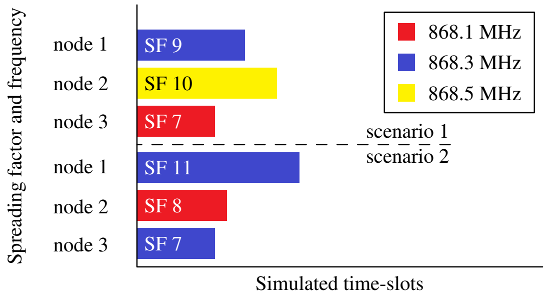

Figure 6. Proposed timeslot channel approach exploiting the LoRa orthogonality feature, adapted from [20].

as the range of spreading factors (7..12), while $N_{CHmax} = 8$ is depicted as the maximum sub-channel frequency bands.

According to work in [20], T_{SL} defines the time-slot of each SF i using a specified frequency channel. The number of time-slots per minute can be annotated to $60 \times timeslot^{-1}$. The theoretical maximum network capacity N can be written as following equation [20]:

$$N = \sum_{SF \in (7,8,9,10)} \frac{60}{T_{SL}(SF)} \times N_{CHmax} \tag{1}$$

The adapted time-slot channel approach demonstrates an evident advantage for LoRa industrial deployment. The method stated in [20] can minimize the packet loss and provide accurate scheduling of the starting point of each transmission. The ns-3 simulation will be performed in section VI by adapting the similar concept of the TSCH approach.

V. Theoretical ns-3 LoRa Model

The theoretical approach must be studied in order to model the simulation behavior closer to the physical LoRa model. The system-level simulation in [13] and [14] are based on two major components as defined in the Vienna Long Term Evolution simulator by [21]. The specification to resemble the actual transmission is explained as follows [13]:

A. Link measurement model

This model aims to compute the signal strength of the receiver side during propagation between the transmitter-receiver pair. The received power level can be formulated as [13]:

$$P_{rx}^{dB} = P_{tx}^{dB} + G_{tx}^{dB} + G_{rc}^{dB} - L^{dB} + 4.34\xi \tag{2}$$

Transmitter gain (G_{tx}^{dB}), receiver gain (G_{rc}^{dB}), transmit power (P_{tx}^{dB}), path loss (L^{dB}), and orthogonal shadowing ($e\xi$) contribute to the estimation of received power (P_{rx}).

The path loss can be categorized into two different factors: *propagation loss* (L_{prop}^{dB}) and *building penetration loss* ($L_{building}^{dB}$). Propagation loss describes the path loss due to the distance between transmitter and receiver. Building penetration loss specifies loss due to external wall loss, internal wall loss, and the fading due to floors and ceilings. The path loss can be expressed as [13]:

$$L^{dB} = L_{prop}^{dB} + L_{building}^{dB} \tag{3}$$

The growing number of end devices in the network affects the distribution of nodes in a particular radius. As a result of it, *correlated shadowing* may occur due to the closeness of one node to another.

B. Link performance model

This model aims to represent the actual implementation of the transmission scenario in the physical layer. The link performance model also estimates the interference that affects the success rate of transmission. Work in [14] shows two significant aspects of this model:

- **Receiver Sensitivity:** As mentioned in Table III-B2b, every SF i contains a different receiver sensitivity level, which can be denoted as S_i. A transmission with SF i has a chance of success if the received power level is greater than S_i. As an assumption in [13], the receiver always locks on the incoming signal and begins to receive the message.
- **SINR Matrix:** The analysis in [13] and [14] explain that interference originates only from other LoRa transmissions. The orthogonality feature of different SF values is considered to model the success rate of packet transmission through despite interference. The SINR matrix is introduced by work in [17] and formulated in equation 4. Both of row and column of Matrix $T_{i,j}$ depict a LoRa device using certain SF values ($SF \in 7, 8, 9, 10, 11, 12$). From equation 4, it is stated that a LoRa transmission with $SF_i = 7$ can survive the interference from another LoRa transmission using $SF_j = 12$, if the SINR of LoRa transmission $SF_i = 7$ is 20 dB stronger compared to another one. Hence, the packet can be correctly decoded by the recipient.

$$\mathbf{T_{i,j}} = \begin{bmatrix} 6 & -16 & -18 & -19 & -19 & -20 \\ -24 & 6 & -20 & -22 & -22 & -22 \\ -27 & -27 & 6 & -23 & -25 & -25 \\ -30 & -30 & -30 & 6 & -26 & -28 \\ -33 & -33 & -33 & -33 & 6 & -29 \\ -36 & -36 & -36 & -36 & -36 & 6 \end{bmatrix} \tag{4}$$

VI. Experiments and Results

The proposed use-case in this paper aims to optimize the yard operation and to synchronize the harbor traffic using localization and tracking methods. Road trucks receive a mobile LoRa-box, which contains a LoRa transceiver and a GNSS receiver. All container shift equipment are permanently fitted with a LoRa-box that captures the asset's location in certain areas. Each LoRa-box transmits the current position of its related asset to the central gateway. `Lorawan` ns-3 module in this scenario is described based on the theoretical model in Section V. To simulate the LoRa communication, a new `Lora` module was developed by D. Magrin [13]. The proposed ns-3 `Lora` module[1] consists of a group of classes that are interconnected and working together to resemble LoRa end nodes and gateway behavior at the various levels of the OSI layer.

A. Experiment scenario

Network Simulator 3 (ns-3) is selected due to its capability to provide a simulation, which is close to physical

[1] Available at https://github.com/signetlabdei/lorawan

implementation. The simulation models and main scripts are defined and linked in C++ objects. Therefore, the simulation experiments of LoRa propagation can be observed precisely. The experimental scenario aims to discover the potentiality of LoRa technology for the harbor use-case.

The conducted simulation was carried out as depicted in Figure 6 by exploiting the pseudo-orthogonality feature. The setup of this simulation defines the total payload size of 29 bytes for both GNSS location and header data. A critical remark is that unconfirmed communication is enabled. Overall, the simulation scenario works as follows: the large number of nodes (N) send packets simultaneously to a single gateway (G) within a fixed radius (r). A single gateway covers the defined area and is located in the central coordinate (0,0) with a height of 15 m above ground. Following are the main steps of the used ns-3 simulation, adapted from [13]:

1) `LoraChannel` *Object Configuration*: The propagation loss model is configured to establish this object class, which is based on [13] and [14].
2) *Creation of End Devices*: the basic ns-3 syntax `endDevices.Create (nDevices)` is applied to create the LoRa nodes.
3) *Assignment of End Device*: the generated end devices are assigned to the uniform random position inside the predefined radius (r) by using `UniformDiscPositionAllocator`. In addition, the end devices' mobility is specified by ns-3 `Mobility` attribute.
4) *Install the LoRa Stack of End Device*: `LoraHelper` class supports to install the LoRaWAN stack to every end device. The setup channel for this scenario is distributed equally into three sub-channels. The nodes are selected randomly to specific sub-channels, which are: three receive paths in 868.1 and 868.3 MHz and two paths in 868.5 MHz.
5) *Creation of Gateway*: the ns-3 `gateways.Create (nGateways)` is defined to establish the gateway in the simulation.
6) *Assignment of Gateway*: the coordinate of a gateway and its mobility are configured by ns-3 syntax `Mobility.SetPositionAllocator` and `Mobility.Install(Gateways)`.
7) *Install the LoRa Stack of Gateway*: the created gateway is linked to the LoRaWAN stack. The receive path allocators are also defined, thus the gateway is able to decode up to 8 messages at the same time.
8) *Create the Buildings*: The class represents a series of building attributes inside the preconfigured radius and yet defaults to the version from [13], where urban building obstacles are assumed for the path loss model.
9) *Set up the SF of each End Device*: Various SF values are assigned optimized to every LoRa node. The assignment can be achieved by calculating the received power at the gateway from deployed end devices in the network.
10) *Install Application on End Devices*: an application is a mandatory setup to establish interaction between end nodes and the gateway. In this simulation, `PeriodicSender` class is implemented to set the delay interval between the start and stop of the simulated transmission in all end nodes.

B. Experimental results

Figure 7 specifies one of the simulation results. The end nodes with specific SF assignment are illustrated as the colored circle points. The color correlates to specific SF values. The gateway is sketched as "GW" symbol in the center of the graph. To adapt the simulation for the harbor environment, an assumption is defined that a series of container stacks represent the yard area of the harbor model. These stacks consist of several stacks of 20 ft containers which are sketched as gray boxes in Figure 7.

1) Scalability performance metrics The first simulation scenario intends to evaluate the network scalability performance of LoRa. The proposed examination was carried out by changing the number of end devices within a fixed radius. A period of 300 s was chosen, i.e., end nodes transmit one packet within 300 s.

The interesting fact from the Figure 7 is that most of the nodes are optimized to use SF 7, which has the shortest time on air (ToA). This behavior is obtained because the simulation mainly focuses on minimizing the ToA to avoid the duty cycle constraints. Figure 9 shows the probability of a successful transmission to be linearly decreasing with a growing number of nodes in the LoRa network. The packets can be decoded successfully by a single gateway. The probability of 93% during the use of 50 nodes then drops to 62.5% for a gateway that serves 5000 nodes.

If less than 500 nodes are deployed, the most significant factor of packet loss is the sensitivity level (see Figure 9). Around 5% of nodes were not able to reach the gateway with satisfactory power level. This is caused by path loss and the reflections in the area. In contrast, when using more than 500 units, more and more network traffic plays a role. Interference is the most dominant aspect for packet loss, where about 10-30% nodes experience interfered propagation with increasing number of nodes. Correlation shadowing, interference due to other LoRa transmissions, inter- and intra-collision contribute

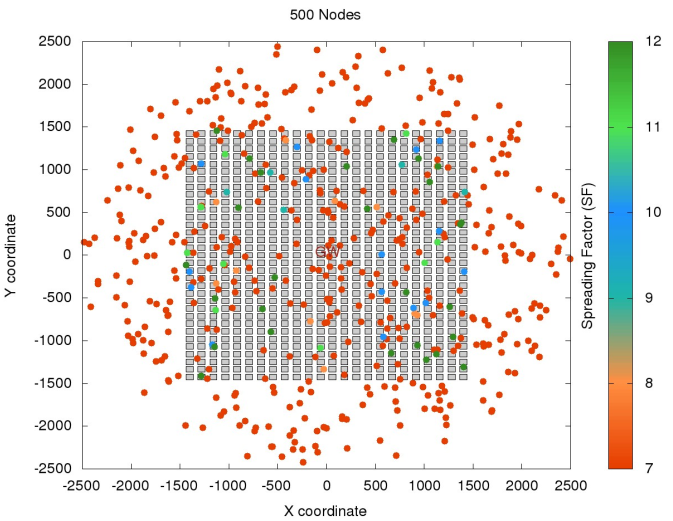

Figure 7. Distribution of 500 LoRa nodes within radius 2500 meters.

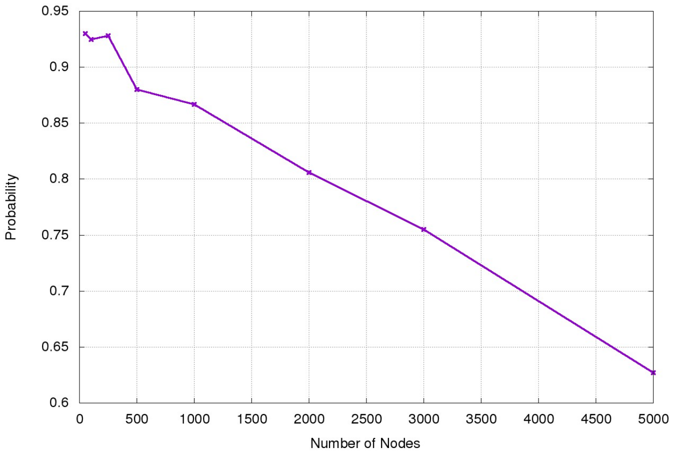

Figure 8. Probability of successful transmission in relation to number of nodes.

to the corruption of packet transmission. In addition, less than 10% of the nodes do not encounter a receiver path at the gateway, because the gateway cannot assign a channel to the end devices due to network congestion.

2) Period length performance metrics The second simulation evaluates the update rate of LoRa to transmit a packet to the gateway. Interval time of the transmission period is an important variable that influences the network traffic. The evaluation was performed by varying the transmission period interval and the number of nodes. The shortest period is 100 s, i.e., every device will transmit a packet once in a 100 s interval. Hence, the greatest throughput among other interval setups can be obtained. Despite its advantage of throughput, this method confronts the duty cycle restriction if we deploy hundreds or thousands of end devices in the LoRa network.

As presented in Figure 10, a downward trend represents the utilization of the 100 s period and at a certain point, the percentage of success transmission drops sharply to 48% for a gateway serving 3000 nodes. As a consequence of increasing the period to 300 s and 600 s, the system performs better with a success rate of 75% and 85% respectively for 3000 nodes. The deployment of nodes less than 250 units proves the best transmission success rate for all period parameters from 90% to 100%. Overall, the best performance is achieved, when the simulation is configured to utilize a 600 s period with the success rate above 85%.

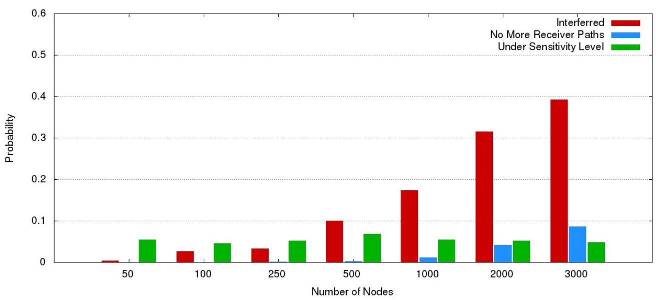

Figure 9. Factors that cause probability of packet loss with respect to number of nodes.

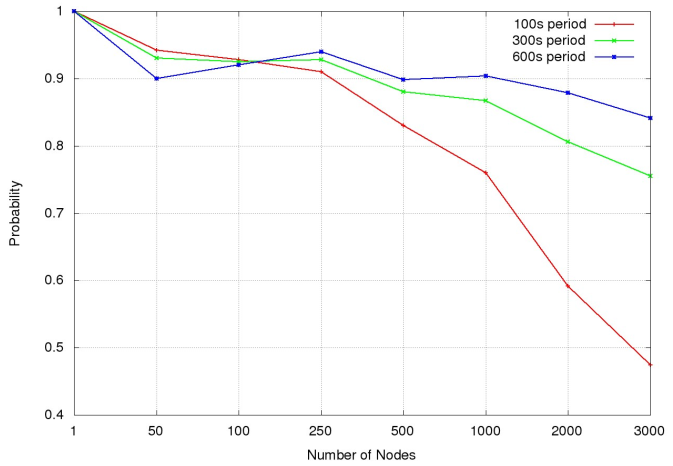

Figure 10. Comparison of probability successfully received packet with different update rate.

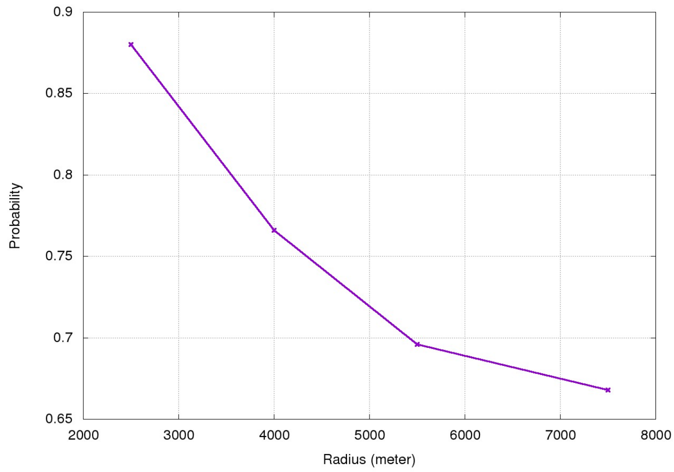

Figure 11. Probability of successfully received packet along with the increasing of the radius.

3) Coverage range performance metrics The final simulation examines the coverage range of LoRa transmissions. The proposed simulation was set up to represent different sizes of harbors. The evaluation was performed to observe the distribution of SF values with various radius parameters. Figure 11 shows the probability for the gateway successfully decoding the received packet, when the nodes are deployed in a radius between 2000 m and 7500 m. E.g., if the radius is less than 5500 m, then probability of received packets is greater than 75%. In addition, a larger radius results in end devices not being able to transmit a packet with sufficient transmission power to the gateway.

Figure 12 illustrates a large number of nodes distributed within an area with radius of 7500 m. As the radius increases, the number of end nodes with SF 7 decreases. Since LoRa implements a trade-off mechanism between data rate and range, the simulation automatically optimizes to select SF greater than 7. More nodes can use higher SF. This result in sufficient coverage range of the area. However, the nodes have longer time on air. This circumstance leads to more collisions in the network due to duty cycle boundary. Hence, it is entirely

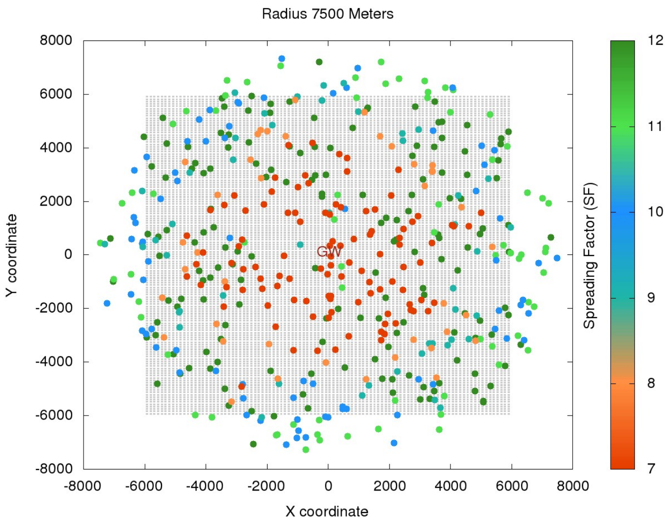

Figure 12. Distribution of end devices with radius of 7500 meters.

coherent with the downward trend of coverage probability concerning the growing number of nodes in Figure 12.

VII. Conclusion

In this paper we evaluated the performance of the LoRa radio technology for geolocation and tracking using ns-3 for a harbor use-case. The first simulation demonstrates the scalability of LoRa device in the network adhering to duty cycle regulations. We found, LoRa scales well to a certain number of nodes. If 500 nodes are deployed in an area spanning a radius of 2500 meters, then the probability of successful transmission is greater than 85%. In this experiment most nodes used SF 7. A gateway serving up to 3000 nodes is able to decode incoming packets successfully with a probability above 75%. Thus, LoRa can scale well up to the thousands number of nodes, depending on the payload size.

In the second experiment, we investigated the relationship between the update rate and the number of nodes under duty cycle regulations. With an update rate of 100 sec, the number of nodes must be limited to 500 to receive data with a probability of above 82%. In the last experiment, we evaluated different coverage area sizes and presented a distribution of nodes with different SF values. The greater distance allows the simulation to optimize end devices using SF > 7. Hereby, nodes that have high SF values are located at the edges and nodes with smaller SF values are located close to gateway. As a result of it, most of the nodes in the network have more time on air and more collisions appear that reduce successful transmissions.

The results presented in the paper show that setting up a LoRa infrastructure in a harbor environment to transfer GNSS data for tracking purposes and geolocation is applicable. However, the user has to derive the appropriate LoRa parameters (like SF value, number of nodes, update rate, and coverage area) according to application and regulations.

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