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EVALUATION OF A NARROWBAND-IOT SYSTEM IN THE TRANSPORT LOGISTICS APPLICATION FIELD

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ABSTRACT

The low level of digitalization in transport logistics is often due to an insufficient understanding of the application possibilities and process implications of digitalization technologies in this context of use. This paper summarizes the results of exemplary investigations of an IoT system with regard to its application possibilities and limitations in transport logistics. Based on the measured variables considered in the tests, conclusions were to be drawn about the connectivity technology Narrowband-IoT (NB-IoT), which forms the basis of this system. For this purpose, different measuring points were defined in the Friedrichshafen area, at which the measured variables of the system under investigation, such as the temperature, the detection of a possible vibration or a free fall of the device, and its position were recorded, documented, and subsequently analyzed. The originality of this contribution lies in the fact that the technology investigation conducted is based on real application scenarios, so that a basis for recommendations and implications regarding technological possibilities within transport logistics can be derived. The results show that embedding the NB-IoT connectivity technology in a corresponding end device enables both the location of the load and the transmission of the load status in urban and rural areas with sufficient accuracy and reliability.

INDEX TERMS Digitalization, Transport Logistics, Narrowband-IoT

CONTENT

ABBREVIATIONS

3GPP .... *3rd Generation Partnership Project*
A-GNSS .... *Assisted Global Navigation Satellite Systems*
AOA .... *Angle of Arrival*
BLE .... *Bluetooth Low Energy*
BW .... *Bandwith*
CID .... *Cell Identification*
CR .... *Coding Rate*
DHBW .... *Cooperative State University*
DL .... *Downlink*
E-CID .... *Enhanced Cell Identification*
EPAL .... *European Pallet Association*
g .... *Gravitational acceleration*
GNSS .... *Global Navigation Satellite Systems*
GPRS .... *General Packet Radio Service*
GPS .... *Global Positioning System*
GSM .... *Global System for Mobile Communications*
IML .... *Institut für Materialfluss und Logistik*
IoT .... *Internet of Things*
LCT-Plus .... *Low Cost Tracker Plus*
LPWAN .... *Low Power Wide Area Network*
LTE .... *Long Term Evolution*
LTE-M .... *Long Term Evolution for Machines*
MAC .... *Media-Access-Control*
NB-IoT .... *Narrowband-Internet of Things*
OTDOA .... *Observed Time Difference of Arrival*
RFID .... *Radio Frequency Identification*
RSS .... *Received Signal Strength*
RSSI .... *Received Signal Strength Indication*
RTLS .... *Real Time Locating System*
RTT .... *Round Trip Time*
SF .... *Spreading Factors*
TOF .... Time of Flight
UL .... *Uplink*
UMTS .... *Universal Mobile Telecommunications System*
Wifi .... *Wireless Fidelity*
WLAN .... *Wireless Local Area Network*

1 INTRODUCTION

The advent of digitalization, especially of networked systems, has been evident in the transport logistics environment for many years. Nevertheless, there is no widespread use of Internet of Things (IoT) [1] applications for tracking and tracing cargo and for identifying the status of cargo in transport logistics [2]. To enable effective and seamless shipment tracking within transport logistics processes, high network coverage is necessary, among other things. This can be ensured by cellular mobile radio, which currently offers the highest availability within Europe and forms the technological basis for a variety of connectivity technologies, including NB-IoT. NB-IoT is a radio-based connectivity technology that is primarily characterized by low cost, low energy consumption, medium range, and low data rate [3]. These characteristics distinguish NB-IoT from other, non-cellular connectivity technologies, such as WLAN, Bluetooth, and Zigbee, which are characterized as suboptimal technology solutions for tracking autonomous, mobile objects in transport logistics applications due to comparatively higher energy requirements and a lower transmission range [4].

The use of connectivity technologies enables the position and status monitoring of mobile objects in transport logistics and thus increases transparency for relevant stakeholders within the transport process. Actors in transport logistics face the challenge of selecting suitable technologies and implementing them in their process to remain competitive through the resulting increase in efficiency and transparency. One major reason for the low use of such mobile devices is the insufficient understanding of the application possibilities and limits of devices available on the market. Another reason is that these technical application possibilities are not specified by concrete use cases in the context of transport logistics applications [5].

This paper addresses precisely this issue by systematically investigating a commercial NB-IoT system to gain an understanding of the potential uses and limitations of this technology for concrete transport logistics use cases.

1.1 RELATED WORK

The experimental evaluation of connectivity technologies (E-C, Fig. 1) and their subsequential comparison is the subject of current research literature. Most frequently, the properties of coverage and energy demand are studied. Other research evaluates, among other things, the delay, and the network capacity (Fig. 2).

For LoRa connectivity technology, related studies are carried out in [6], [7] and [8]. As an example of this, Petajajarvi et al in [7] investigate the network coverage of LoRa connectivity technology in practical experiments on land and water in the city of Oulu in Finland. For this purpose, LoRa devices available on the market that are moved by car and boat send data packets with a sequence number and the GPS coordinates to a permanently installed base station. Based on this, the packet loss rate is then determined and displayed on a heat map. The study shows that LoRa enables reliable transmission of data over certain distances in defined environments, but the experiments are not based on any specific application scenarios.

Similarly, in [9], the coverage of GPRS, Narrowband-IoT, LoRa and SigFox technologies is studied and compared. In addition to coverage, Ballerini et al [10] evaluate NB-IoT and LoRa connectivity technologies, also in terms of energy consumption and packet loss rate. Based on this, the technologies are compared with each other and based on service quality, network coverage and costs, application recommendations are made for the areas of manufacturing automation, supply chain management and monitoring and maintenance. Compared to the studies mentioned above, the experiments in [10] are thus related to concrete application areas. However, they do not cover explicit transport logistic scenarios.

Further investigations regarding the use of connectivity technologies in different environments and shielding scenarios are conducted in [11], [12], [13] and [14]. For example, in [13] NB-IoT, LTE Cat-M1, Sigfox, and LoRa connectivity technologies are investigated for their reliability for data transmission on land and in the air. In [14] Lombardo et al compare NB-IoT and LoRa technologies in terms of the effect of underwater, underground, and metal shielding on data transmission. The indoor application of NB-IoT is studied in [15].

In [16] the reliability of NB-IoT when applied within an IoT system is investigated by evaluating, among other things, the effects on data transmission by changing the distance between transmitter and receiver nodes, the number of signal nodes within the network, and the shielding.
These investigations also refer to the change of certain experimental parameters, such as the transmission distance or the shielding. However, there are no concrete application scenarios and no reference to transport logistics.

The use of connectivity technologies is discussed in the research field of transport logistics (C-T, Fig. 1) in different contexts, such as tracking of objects, monitoring of the condition of loads, which plays a significant role especially in refrigerated supply chains, indoor positioning, vehicle monitoring, and tracking applications. Tracking of loads using RFID technology is an application area that is being researched in [17], [18] and [19], among others. As an example of this, Kim and Hong [17], deal with possibilities to optimize maritime transport logistics by using IoT technologies. The authors present a real-time location system for building an intelligent container terminal management system. This is based on data collected using RFID tags, RTLS tags, and sensor tags, which are synchronized and processed for users using a middleware platform. Experimental investigations on the feasibility of the system are not carried out.

Feng et al [20] present an intelligent tracking system for campus bus transportation. Within the system, RFID connectivity technology is used for localization, tracking, and monitoring of the buses. Furthermore, ZigBee is used for data transmission between the vehicle, the bus stop and the monitoring center. Intelligent bus scheduling is then simulated based on the simulated-annealing algorithm, but not tested in practice.

In [21] and [22], the suitability of NB-IoT for monitoring refrigeration supply chains is investigated. Wanganoo et al [21], for example, present a concept for improving the transparency of refrigerated supply chains, especially regarding last-mile delivery, using NB-IoT. By equipping containers and pallets with NB-IoT modules, which enable real-time transmission of temperature, humidity, position, vibration, and other data collected by sensors to an IoT platform, the cargo is monitored, and automated notifications are sent to indicate any deviation of the collected data from a defined standard.
Thus, if necessary, measures can be initiated before the quality of the goods is affected. Within the scope of the thesis, the presented concept was described in terms of hardware and software, but it has not yet been tested in the field.

Song et al [23] address the application of IoT technologies in smart logistics based on the underlying technologies, such as RFID, BLE, Wifi, and Zigbee, among others. They describe how the technologies work and discuss the use cases in which they can be used to solve logistics problems, such as in the areas of transportation, warehousing, loading, and unloading, and distribution.
Regarding the application field of transport logistics, possible applications for monitoring the vehicle, the goods and the driving behavior of the person driving are mentioned, among other things, whereby the collection and transmission of the location and speed of the vehicle, sensor data for monitoring the goods and other information is necessary. The authors describe the potential applications of the technologies in theory, but do not conduct any research to evaluate the technologies in practice.
There is a small body of work that focuses on the experimental investigation of connectivity technologies in the context of transportation logistics (I, Fig. 1).

A comparison of BLE, Wifi, ZigBee, and LoRa technologies with respect to their suitability for indoor localization is performed by Sadowski and Spachos [24]. In each case, the position accuracy is determined with the aid of RSSI value and trilateration as well as the energy requirement. Nine tests are carried out in two test environments (research lab, meeting room) in which different distances between transmitter and receiver and different positions are set. The experiments show that under certain conditions Wifi has the highest accuracy, BLE the lowest energy demand and LoRa the longest range in a comparison of the technologies. Furthermore, the results indicate a suitability of the technologies for the purpose of indoor localization.

The connectivity technology LoRa is investigated by Murillo et al [25] regarding its suitability to tracking applications within transport logistics. LoRa end devices and a gateway are used within an intelligent tracking system and, among other things, the parameters spreading factor (SF), bandwidth (BW) and coding rate (CR) are determined, whereby both the distance between gateway and end device and the number of devices are varied.
Based on this, the optimal parameters for data transmission within the system are determined. In this study, experimental investigations are conducted in a transport logistics context, but using LoRa connectivity technology.

In a Europe-wide field study on the use of LPWAN technologies, the Fraunhofer Institute, IML, Dachser, and EPAL investigated the reliability of the technologies NB-IoT, Sigfox, and LTE-M for data transmission in transport logistics applications. Furthermore, the 2G (GSM) and 3G (UMTS) mobile radio standards were used for a holistic view, so that their technological differences in terms of data rate, frequency range, energy consumption, and range could be made visible and their application-specific advantages and disadvantages could be highlighted. Based on the project results, the researchers recommend a combination of classic mobile radio and LPWAN technologies to ensure reliable data transmission within Europe. The latter is predicted to be future-oriented connectivity technologies in the transport logistics context [26].

Among other things, forecasts such as that of the Fraunhofer Institute illustrate the relevance of research into the possible applications and limits of LPWAN technologies in transport logistics [26]. The literature considered indicates that research into the properties of connectivity technologies (E-C), as well as possible concepts for their use in transport logistics (C-T), is of relevance in the current scientific context. Literature at the interface between transport logistics and experimental research (T-E) was not considered due to its minor relevance for the present study (Fig. 1).

An overview of the literature considered is shown in Fig. 2. Their analysis shows that the connectivity technologies LoRa and NB-IoT are most frequently considered. Coverage and power requirements are the subject of research in most studies, while the motion detection and temperature monitoring suitability evaluated in this study have not been considered so far. By far the most frequently considered application scenario within transportation logistics is tracking.

However, a combination of these research aspects (I, Fig. 1) and thus the investigation of the suitability of specific NB-IoT end devices within different, defined, transport logistics case studies has so far only been considered sporadically in the literature and has been insufficiently documented to be able to make recommendations for action for actors in transport logistics.

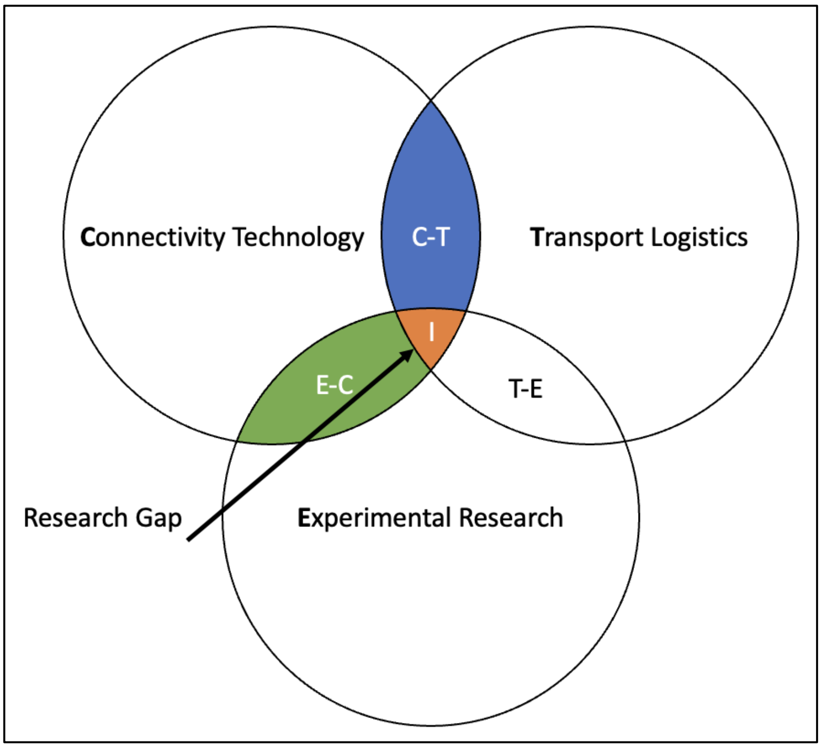

FIGURE 1. Intersections of the literature considered in the fields of connectivity technology, transport logistics and experimental research.

Area	Connectivity Technology											Experimental Research						Transport Logistics			
	NB-IoT	BLE	WLAN	Cellular	LTE-M	RFID	ZigBee	Sigfox	LoRa	NFC	GPRS	Motion Detection	Position	Tempe-rature	Energy Consumption	Coverage	Delay	Freight Condition Monitoring	Indoor Localization	Vehicle Status Monitoring	Freight Tracking
E-C									[6]						[6]	[6]					
									[7]							[7]					
									[8]						[8]	[8]					
	[9]							[9]	[9]		[9]					[9]					
	[10]								[10]						[10]	[10]					
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%	47.6	9.5	9.5	4.7	9.5	23.8	14.2	23.8	52.4	4.7	4.7	0	4.7	0	28.6	66.6	14.2	19	9.5	9.5	42.9
This Paper	x											x	x	x				x			x

FIGURE 2. Summary of the considered literature based on the mentioned intersections.

1.2 RESEARCH OBJECTIVE AND RESEARCH QUESTION

To address this research gap accordingly, this paper analyses an NB-IoT system solution available on the market as an example in defined use cases to evaluate the application possibilities and limitations of this device in the context of transport logistics.
To achieve this declared research goal, the following central research question will be answered:

Central research question: What are the possible uses and limitations of the specific narrowband IoT terminal in the application field of transport logistics?

By decomposing this overarching research question (RQ) into sub-questions, a granular basis for the present research contribution can be achieved.

RQ 1: Which use cases and corresponding measured variables are relevant for transport logistics tasks to realize condition monitoring of mobile objects, such as load carriers or loads?

RQ 2: What possible applications, limits, and implications can be derived for the connectivity technology Narrowband IoT, based on the end device examined, for exemplary transport logistics tasks?

1.3 THEORETICAL BACKGROUND AND DEVICES USED

The IoT device examined in the research is the Low Cost Tracker Plus (LCT-Plus), from Deutsche Telekom IoT GmbH. The device is equipped with the cellular mobile radio technology NB-IoT, which enables communication and data transmission to surrounding radio cells. Data is transmitted from the respective radio cells to a network server. Downstream of the network server are application servers of the system providers, on which the transmitted data of the end devices are aggregated. The mobile device is embedded in a system that displays the communicated data in a back-office software utilizing a dashboard application (Fig. 3).

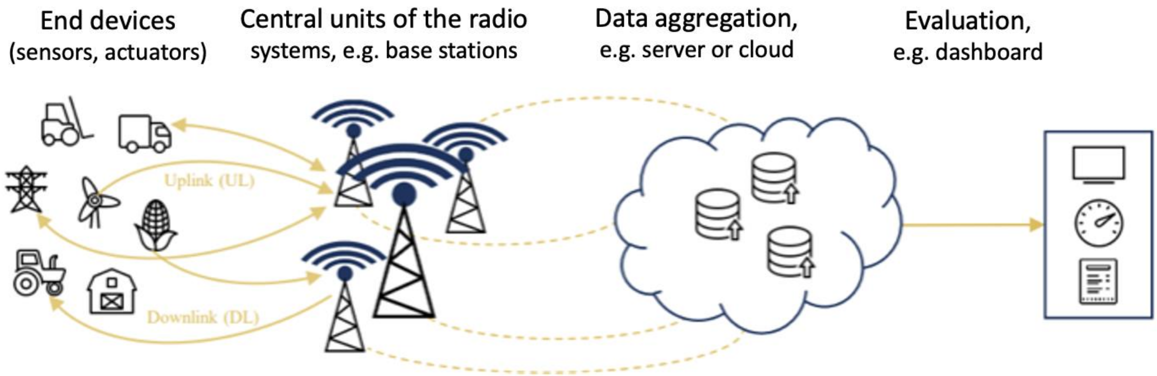


FIGURE 3. Architecture and components of LPWAN technologies in generalized representation [46].

NB-IoT is a Low Power Wide Area Network (LPWAN) technology introduced in 2016 by the 3rd Generation Partnership Project (3GPP). It coexists with the licensed frequency bands of the Global System for Mobile Communications (GSM) and Long-Term Evolution (LTE), e.g., 700 MHz, 800 MHz, 900 MHz. Due to this, there are different operation modes: in-band usage, guard-band usage and a standalone usage [27]. The bandwidths used by NB-IoT are 180 kHz for in-band and guard-band use and 200 kHz for stand-alone use (Fig. 4) [28].

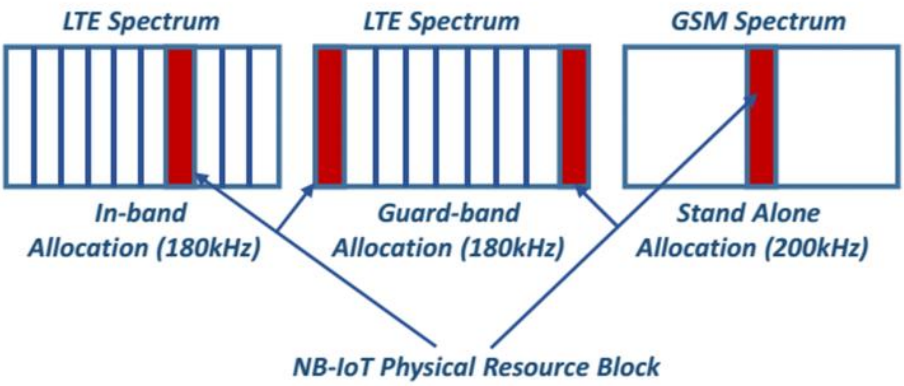


FIGURE 4. NB-IoT deployment scenario (i.e., in-band and guard-band) and when Re-farming the GSM Spectrum (standalone) with reference to [29].

The network architecture of NB-IoT is arranged in a star configuration. End devices are connected directly to the base station, eliminating the need for gateways and relays and resulting in both cost and energy savings. The latter result from the fact that the devices do not have to constantly listen to other devices to determine whether data should be forwarded through them. The base station always remains switched on in the case of a star network topology to allow end devices access at all times [29].

Approx. 50,000 devices can be connected per cell. The supported data rate is 200 kbps in the downlink (DL) and 20 kbps in the uplink (UL). A maximum data size of 1,600 bytes can be sent per message. [30]. NB-IoT is thus suitable for transmitting data in various devices, such as sensors, meters, asset trackers and wearables. Therefore, the technology is used in a wide range of industries, such as smart city planning, healthcare and agriculture, among others. [29].

Coverage is defined by the signal strength and the quality of the radio frequency and can be expressed, among other things, by the maximum coupling loss. This indicates how high the loss of signal strength between the transmitter and receiver can be without the connection being broken. Factors that affect the maximum coupling loss include the distance of the transmitter to the base station as well as the surrounding terrain, surrounding buildings and other obstacles [30]. The maximum coupling loss of NB-IoT is 164 dB [31]. This allows data to be transmitted over a maximum distance of 20 km [32].

In addition to network coverage, the energy requirement is also a decisive criterion for selecting a technology. With a maximum coupling loss of 164 dB, a battery life of 10 years can be achieved for data transmission using NB-IoT if 200 bytes are sent per day on average [33].

The advantages of NB-IoT are thus primarily high network coverage, low energy requirements and support for connecting a large number of devices. On the one hand, the limited data rate, which is crucial for the speed of data transmission and thus limits the use of the technology for areas with low transmission speed requirements, can be considered a disadvantage of the technology. On the other hand, the licensed spectrum can be considered a disadvantage due to possible costs [32]. Table 1 summarizes the key specifications of the technology.

Parameter	NB-IoT
Standardization	3GPP
Frequency Bandwith	Licensed LTE or GSM, 700, 800, 900 MHz
Bandwidth	Min. 180 KHz
Data rate	Uplink: 20 kbps Downlink: 200 kbps
Max. payload length	1.600 bytes
Maximum coupling loss	164 dB
Range	< 20 km
Battery	10 years (avg. 200 byte per day, 164 dB)

TABLE 1. Key specifications of NB-IoT.

The low-cost tracker investigated in this study is a mobile data collection device that is used in the logistics sector to track the position, as well as monitor the conditions, of containers, pallets, and packages, among other things. The device works based on a combination of connectivity technologies, such as 2nd generation cellular mobile radio (2G), NB-IoT, Bluetooth Low Energy (BLE), and Wireless Local Area Network (WLAN). The position is not determined by GNSS modules or similar, as the position of the device is determined using the radio technologies described. The LCT-Plus is also equipped with an acceleration sensor and a temperature sensor. This enables the recording of further relevant data in logistical application scenarios. The processing of the recorded data is carried out by the embedded microcontroller, which is supplied with power by the battery. The modular structure of the Low Cost Tracker Plus is shown in Figure 5.

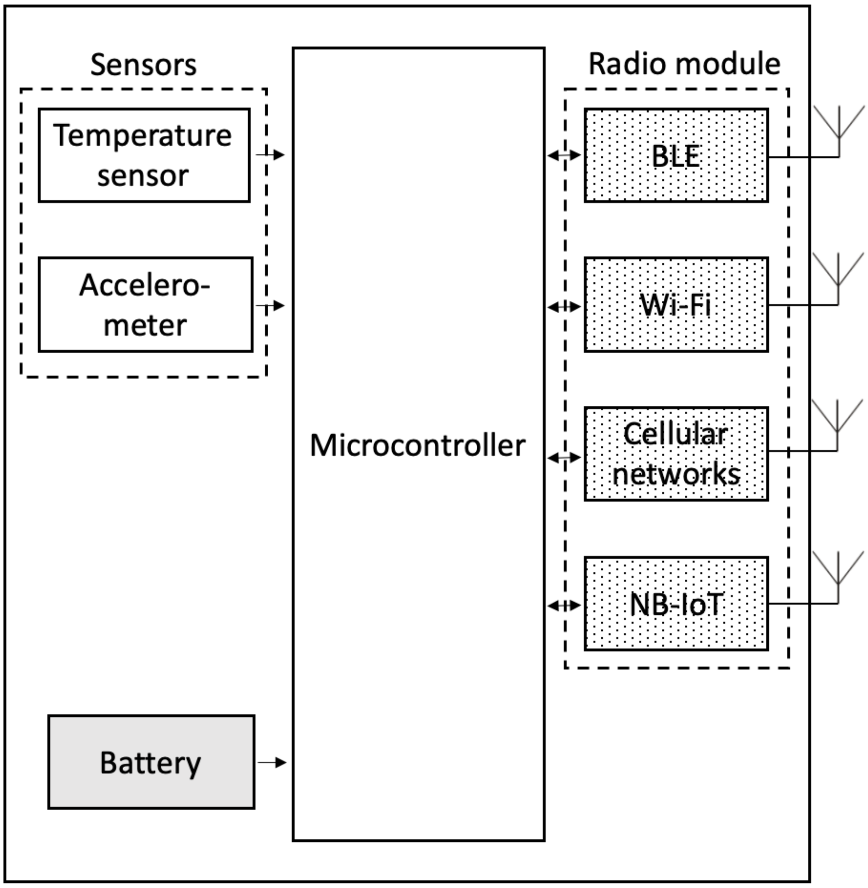


FIGURE 5. Block Diagram Low Cost Tracker Plus

In practice, three different calculation methods, Enhanced Cell-ID (E-CID), Observed Time Difference of Arrival (OTDOA), and Assisted Global Navigation Satellite Systems (A-GNSS), are used to determine positions using the LTE mobile radio standard, to which the NB-IoT radio technology also belongs (Table 2) [34].

Method	LTE-based	Satellite-based	Hybrid method
E-CID	X		
OTDOA	X		
A-GNSS			X
GNSS		X	

TABLE 2 Position determination methods [34].

With the Cell-ID method (CID), the position of an object is determined based on the radio cell in which the device to be located is dialed in. The accuracy of the position measurement depends on the size of the respective radio cell, which in urban areas is between 200 m and 1 km and in rural areas between 35 km and 100 km [35]. The smaller a radio cell is, the more precisely the position can be determined. The E-CID method builds on this principle and calculates the position by measuring different types of distance and signal strengths in relation to the respective base station. These measurements include Round Trip Time (RTT), Angle of Arrival (AOA), and Received Signal Strength (RSS). The E-CID method is often used as a fallback level when it is not possible to determine a position using GNSS or WiFi [35].

The downlink-based position determination method Observed Time Difference of Arrival is assigned to the 3GPP standard. This method corresponds to multilateration, in which the propagation times of the signals between a base station and a terminal are measured to determine the prevailing distance between the base station and the terminal. In the multilateration method, the measured distance between a respective base station and the terminal is subtracted from the measured distances between a reference base station and the terminal. This results in geometric ellipses that meet at an intersection point corresponding to the position of the terminal (Fig. 6) [36].

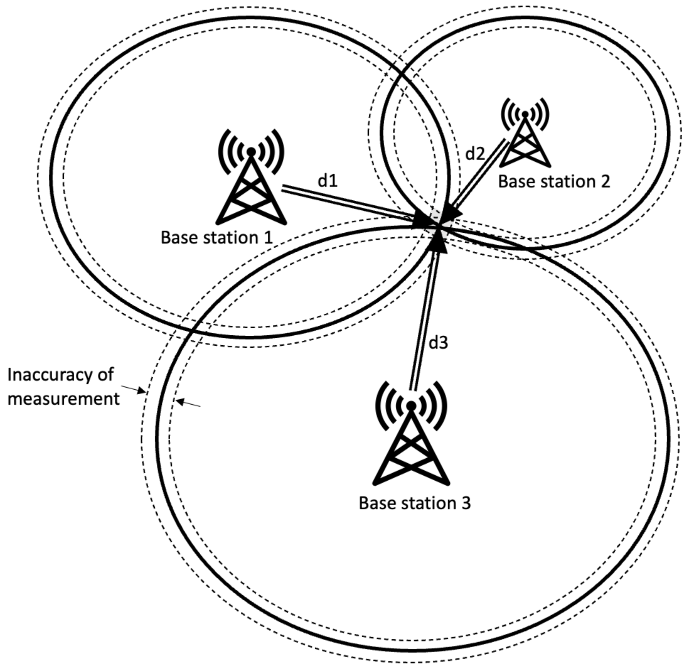


FIGURE 6. Multilateration using time-of-flight (TOF) measurements with reference to [37].

From this approach of multilateration, a linearized system of equations can be developed, which contains the searched position $\vec{x} = [x \quad y]^T$ of the end device and the positions of the base stations $\vec{x_i} = [x_i, \quad y_i]^T$ (cf. (1)) [37].

$$d_i^2 = (x - x_i)^2 + (y - y_i)^2 \qquad (1)$$

$$, where\ d_{i\ll<} = distance\ between\ base\ station\ and\ end\ device$$

In a planar position determination method, a linearized system of equations can be derived based on a reference base station and two further base stations (cf. (2)), which contain the sought position of the terminal. This position of the terminal can be calculated by appropriate mathematical solution methods. By adding further base stations and a procedure such as the method of least squares, theoretically better position accuracies can be achieved [37].
However, this is often not easy to implement in practice, as parameters such as transmission range and network coverage are strongly limiting technical factors.

$$\begin{bmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y \end{bmatrix} \cdot \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} d_1^2 - d_2^2 - k_1 + k_2 \\ d_1^2 - d_3^2 - k_1 + k_3 \end{bmatrix} \qquad (2)$$

$$, where\ k_i = x_i^2 + y_i^2$$

The Global Navigation Satellite System (GNSS) forms the basis for position determination using the A-GNSS method. The terminal to be located receives the time and position data from at least four different satellites and determines its position in relation to three of these satellites by converting the time required for signal transmission. Additional satellites are used to compensate for the clock error to increase the position accuracy [38]. In this way, it is possible to determine the position of the object without using terrestrial networks. The Assisted-GNSS method builds on this principle. Through the additional reception of mobile radio data ("assistance data") and the associated radio cell-based approximate localization, the process duration and the energy requirement of the localization are reduced [39].

The location of the Low Cost Tracker Plus is determined by a combination of different radio technologies, each of which enables a position to be determined with varying precision (Table 3). The position is indicated in the dashboard through longitude and latitude.

Radio Technology	*Positioning Accuracy*
2G	*1-5 km*
NB-IoT	*35 km*
WLAN	*50 m*
BLE	*< 1 m*

TABLE 3. Comparison of different ratio technologies concerning positioning accuracy.

Furthermore, the device is equipped with sensors for recording temperature (°C) and acceleration (m/s2) as well as the state of a free fall. The acceleration and free fall are measured based on the representation of changes in the state of motion in the form of discrete signals [40].

1.4 RECORDED MEASUREMENTS IN RELATION TO TRANSPORT LOGISTICS

In this section, the recorded measured variables are presented and their relevance in the application context of transport logistics is discussed. The relevance of the measured variables recorded for the condition monitoring of mobile objects results from the specific application scenarios.
The measured variables recorded in this study are based on the measurement equipment of the low-cost tracker used and are as follows:

- Temperature
- Motion detection
- Positioning

Examples of areas of application in which knowledge of the status of the load is important include picking and order management, end-to-end transport monitoring, general process optimization, and preparation for the receipt of goods by announcing the goods based on real-time data.

Monitoring the temperature of the cargo or the hold plays a major role in the quality assurance of temperature-sensitive or perishable goods. As has already been shown in the literature, the food and pharmaceutical industries are particularly important as a field of research and application. Depending on the transported goods, different requirements are placed on the technologies used to monitor their condition. Real-time monitoring of the goods makes it possible to initiate preventive measures to regulate the temperature to avoid damage to the cargo. Furthermore, the need for human labor regarding controlling the temperature in the cargo hold can be reduced by automatic sensor and control technology. Thus, the use of suitable systems can increase transparency in the transport process and reduce reaction time.
Motion detection is used to transfer the device from sleep mode to active status. A threshold value is defined that corresponds to an initial movement, which is interpreted as the start of the movement and thus marks the beginning of the transport. In this way, data is not sent permanently, but at a specified time interval to reduce the amount of data to a manageable level and also not to excessively affect the battery life.

Settings such as the threshold value for motion recording and the time interval of data transmissions can be made by the system user in the corresponding back-office application. A special case of motion detection is the detection of the free fall of a load. This data can be used, for example, to conclude the causes of possible damage, which is of great importance regarding insurance and warranty claims.
In addition to temperature monitoring and movement detection of a consignment, the position of the vehicle or the consignment represents elementary information within transport logistics. Position monitoring is a widely known task for dispatchers, as the information regarding the truck or load position is an important component in terms of process transparency. Especially with the emergence of reactive planning measures, knowledge of vehicle and load position is critical to success. Locating the vehicle's position is an established task that is already solved confidently by a GPS module and a data transmission interface via the vehicle's telematics unit, both for the tractor unit and the trailer. However, determining the position of the load is a young field, as the energy supply for a GPS module is not a simple task for mobile objects. Furthermore, the loads are located inside the cargo hold during transport, which precludes positioning utilizing satellites, as there is no line of sight between the receiver module of the load and the satellites.
With the advent of IoT technologies, it is possible to determine the position at the load level. This makes it possible for dispatchers, for example, to carry out a position comparison between the truck and the load if the truck is loaded incorrectly, to be able to initiate appropriate reactive measures in good time and to avoid incorrect transport.

2 METHODOLOGICAL APPROACH

This section describes the steps for the practical implementation of the experiments. These include defining the measuring points, carrying out the reference measurements, and then the final measurement of the described measured variables.

2.1 DEFINING THE UNDERLYING MEASUREMENTS AND MEASURING POINTS

The test area of the study is in the Friedrichshafen area (Lake Constance district, southern Germany) and includes both rural and urban areas [41]. In addition to the superordinate categories, rural and urban, the four subcategories, city, nature, building, and lake, were formed with corresponding intensity gradations to describe the surroundings of the measuring points (Table 4).

	Influencing Factors			
	City	***Nature***	***Buildings***	***Lake***
Factor Levels	Urban	No forest	No buildings	No lake
	Rural	Near the forest	Very few buildings	Close to the lake
		Forest	Few buildings	Directly at the lake
			Many buildings	

TABLE 4. Factors for defining the measuring points.

Using combinatorics, 72 possible combinations of the environmental factors can be determined (Table 5). However, some of these combinations are excluded, such as the combination of the factors "urban" and "no buildings" or "very few buildings". Furthermore, some combinations can be found, but not within the described test field. Due to these limitations, the number of representable combinations of environmental factors decreases to 27.

For the systematic execution of the investigations, the area was divided into four equidistant, concentric measurement areas at 5 km from each other (Fig. 7). The concentric circles, which represent the measurement areas, are centered on the Friedrichshafen technology campus of the Baden-Württemberg Cooperative State University (DHBW) in Ravensburg.

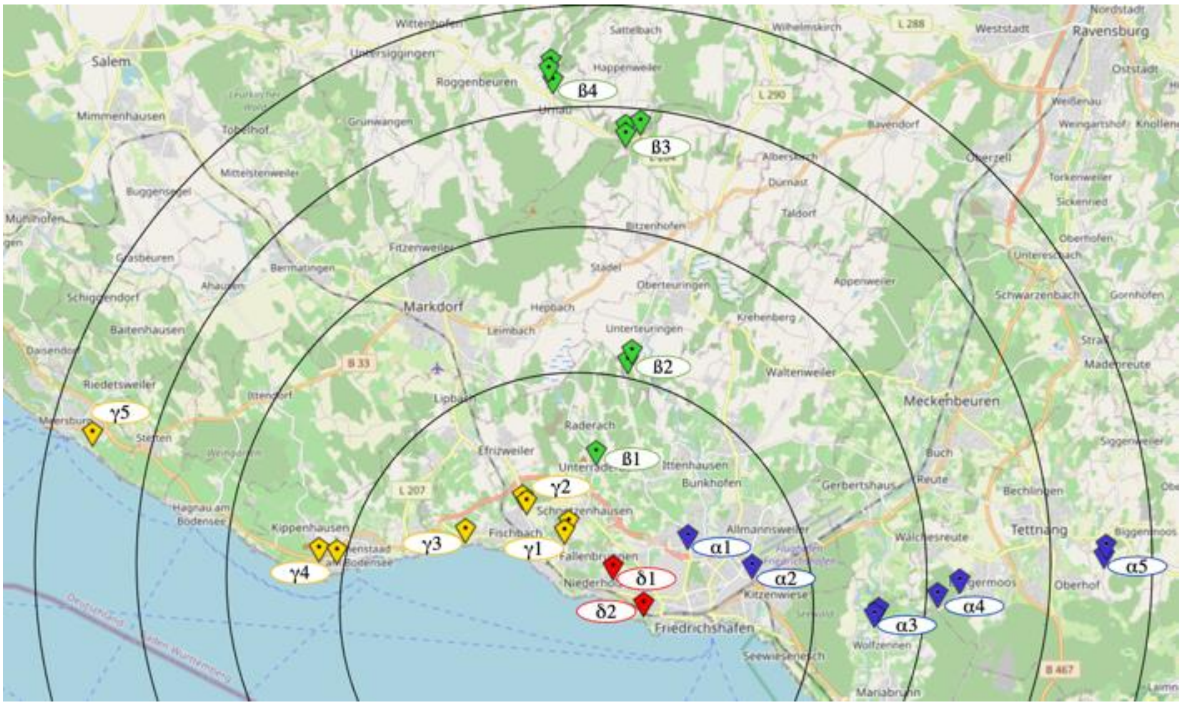


FIGURE 7. Measuring points for examining the position accuracy.

Since the accuracy of the position determination also depends on the network coverage, it was ensured that areas without network reception, with 2G mobile radio standard and with 4G mobile radio standard were both within the test field (Table 5) to ensure comparability of the measurement results regarding the accuracy and speed of data transmission. In addition, a shielding of 35 dB (99.97 %) was simulated with the help of an armoring fabric. This scenario corresponds, for example, to the conditions in shielded environments such as containers and basements.

Measuring point - network coverage	**GPS-Coordinates**	**Description**
γ1-2G	47.670060, 9.43579	urban, no forest, few buildings, no lake
γ1-4G	47.668147, 9.434282	urban, no forest, few buildings, no lake
γ2-2G	47.675735, 9.421166	urban, no forest, few buildings, no lake
γ2-4G	47.674428, 9.422050	urban, no forest, few buildings, no lake
γ3-4G	47.668377, 9.401997	rural, forest, no buildings, close to the lake
γ4-4G	47.664181, 9.354266	urban, no forest, many buildings, close to the lake
γ4-4G	47.663622, 9.360271	urban, no forest, many buildings, close to the lake
γ5-4G	47.689514, 9.280698	urban, near the forest, few buildings, directly at the lake
β1-4G	47.685439, 9.444658	rural, near the forest, few buildings, no lake
β2-2G	47.705463, 9.454831	rural, near the forest, few buildings, no lake
β2-4G	47.707571, 9.456166	rural, near the forest, few buildings, no lake
β3-2G	47.756980, 9.454130	rural, forest, no buildings, no lake
β3-4G	47.755194, 9.454163	rural, forest, very few buildings, no lake
β3- no network	47.757999, 9.459204	rural, forest, very few buildings, no lake
β4-2G	47.769516, 9.429139	rural, forest, no buildings, no lake
β4-4G	47.766945, 9.430505	rural, forest, no buildings, no lake
β4- no network	47.771112, 9.429369	rural, no forest, no buildings, no lake
α1-4G	47.666823, 9.474684	urban, no forest, many buildings, no lake
α2-4G	47.660296, 9.495115	urban, no forest, many buildings, no lake
α3-2G	47.649746, 9.535215	rural, near the forest, no buildings, no lake
α3-4G	47.650971, 9.536839	rural, forest, no buildings, no lake
α4-2G	47.654148, 9.555989	rural, forest, no buildings, no lake
α4-4G	47.657272, 9.563073	rural, near the forest, no buildings, no lake
α5-2G	47.662696, 9.610222	rural, no forest, no buildings, no lake
α5-4G	47.664815, 9.610792	rural, no forest, no buildings, no lake
δ1-4G	47.660142, 9.449987	urban, no forest, few buildings, directly at the lake
δ2-4G	47.652027, 9.460230	urban, no forest, few buildings, close to the lake

TABLE 5. GPS coordinates and description of the measuring points.

2.2 CARRYING OUT THE REFERENCE MEASUREMENTS

Before the actual measurements can be tackled, reference measurements are used to create a basis for comparison for the interpretation of the actual measured values. In this way, corresponding statements can be made about the accuracy of the Low Cost Tracker Plus regarding position determination and temperature measurement. The reference measurements of these two parameters form the basis for the subsequent evaluation of the tests and the resulting implications regarding the suitability of the device for use. The procedures described below for the respective reference measurements were all carried out at the previously described measuring points (Table 5) to ensure consistent comparability between the reference and actual measured values.

A mobile GPS module is used as a comparison device to determine position accuracy. The device receives a high bandwidth of satellite signals and calibrates them simultaneously with the help of a fixed reference point via the mobile network. This fixed reference point continuously provides correction data employing real-time telematics (RTK) and thus enables a positional accuracy of up to 1.4 cm deviation from the real position (Fig. 8) [42].

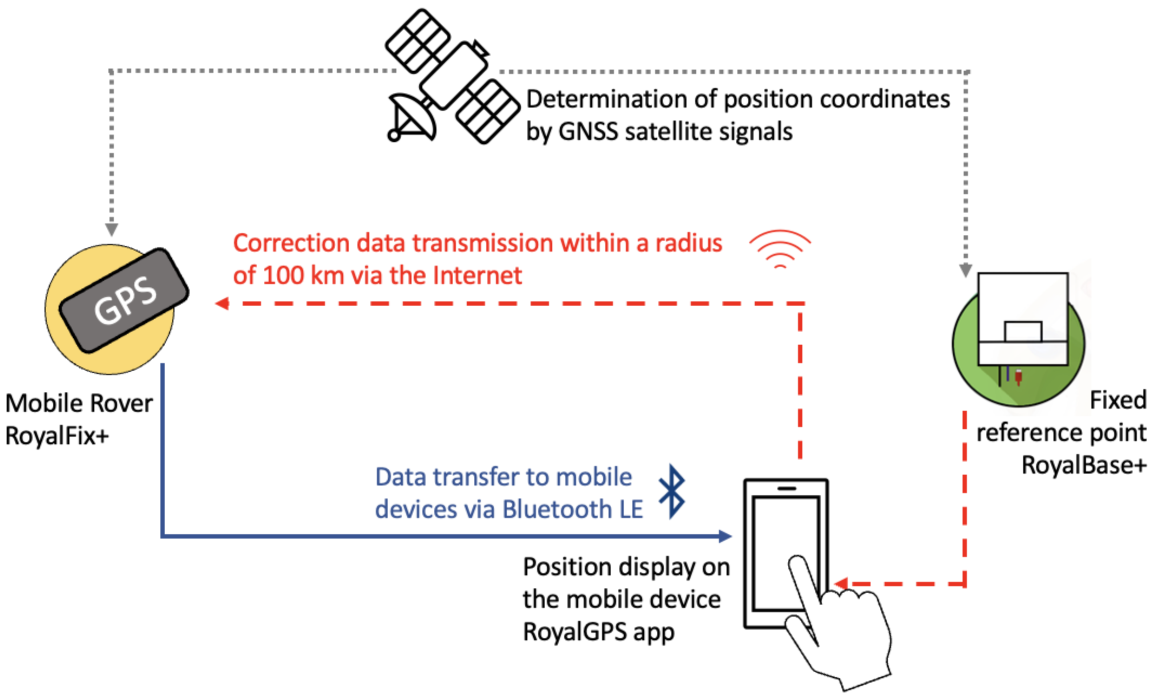


FIGURE 8. Functional scheme of the position reference measurement system based on [42].

A respective reference value of the real position is collected by installing the GPS module at a previously defined measuring point using a tribrach and triggering the measurement. The device transmits the exact location coordinates, the time of the measurement, and further information, such as the number of satellites received, to the mobile software application of the measurement system. Each measurement position is documented photographically so that the exact correspondence of the measurement points in the reference measurement and the measurement with the Low Cost Tracker Plus can be guaranteed (Fig. 9).

FIGURE 9. Experimental set-up of the reference measurement.

The reference measurement to check the measurement accuracy of the temperature sensor is carried out with an RC-5 temperature data logger, which ensures a measurement accuracy of +/- 0.5 °C within a temperature range between -30 °C and 70 °C. Since both reference and main ambient temperature measurements are performed simultaneously, the procedure is explained in more detail in the following section.

2.3 CARRYING OUT THE MEASUREMENTS

2.3.1 POSITION MEASUREMENT

The aim of position measurement using a Low Cost Tracker Plus is to determine the deviation in position accuracy relative to the reference measuring device. Analogous to the reference measurement, the tribrach is set up at the previously photographically documented position, the Low Cost Tracker Plus is placed on the tribrach and then the measurement is carried out and documented. In case simultaneous measurements by the reference measuring device and the LCT-Plus are possible, this is preferably aimed at and carried out (ideal solution, Fig. 10). Since the reference measuring device and the LCT-Plus are not available at the same time in the present investigation, the reference measurement by the LCT-Plus is carried out upstream (alternative solution, Fig. 10).

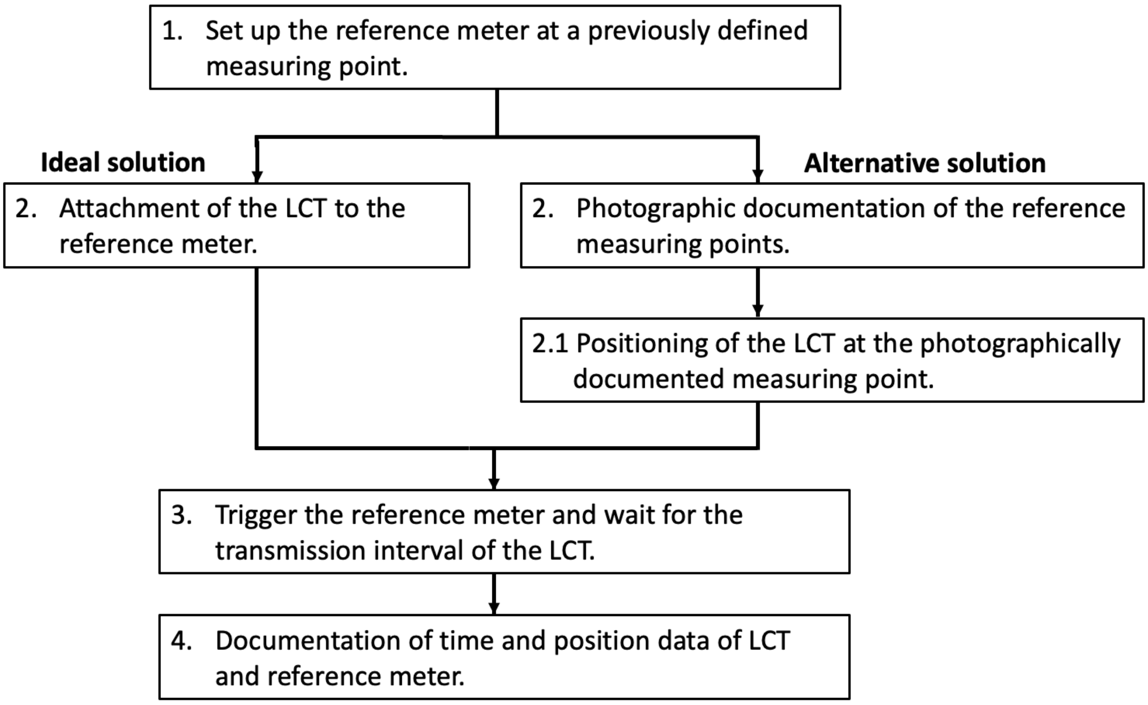


FIGURE 10. Experiment procedure of the position measurement with the LCT-Plus.

2.3.2 TEMPERATURE MEASUREMENT

To investigate the temperature measurement, the Low Cost Tracker Plus and the reference measuring device are positioned simultaneously in a package box. The package box is chosen with the background of minimizing possible interferences of the environmental situation and ensuring a reliable measurement with low temperature fluctuations. After an acclimatization period of 15 minutes, the measurements are triggered and the results as well as the time of the measurement are documented. The recording of the temperature readings of the data logger are averaged and act as a reference measurement. The deviation between the LCT-Plus and the reference measuring device is then determined based on the data obtained (Fig. 11).

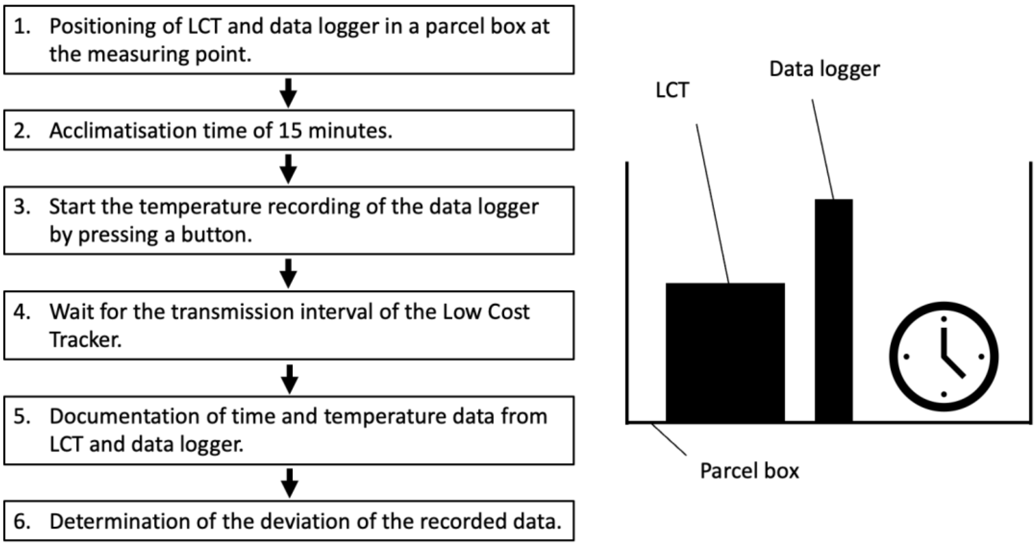
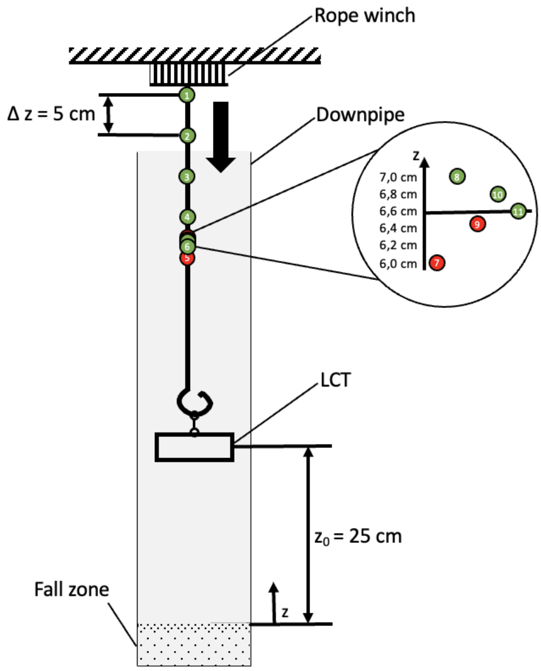


FIGURE 11. Experiment sequence of the temperature measurements.

2.3.3 DROP TESTS

A laboratory test is carried out to determine the lowest drop height that allows the Low Cost Tracker Plus to detect a free fall. To perform the experiment, a downpipe with a rope winch is used to set different drop heights. The fall zone is at the bottom end of the downpipe. The Low Cost Tracker Plus is attached to a rope which is marked at defined intervals to determine the height of fall (Fig. 12).



Point	Corresponding fall height of the LCT	Detection of free fall?
P1	25 cm	√
P2	20 cm	√
P3	15 cm	√
P4	10 cm	√
P5	5 cm	X
P6	8 cm	√
P7	6 cm	X
P8	7 cm	√
P9	6,5 cm	X
P10	6,8 cm	√
P11	6,6 cm	√

FIGURE 12. Schematic experiment set-up for free-fall measurement.

Starting from an initial drop height of 25 cm, this is reduced by 5 cm after each successful detection of free fall. If the free fall is no longer detected after the reduction of the fall height, the fall height is successively adjusted in reduced increments of 2 cm, 1 cm, 0.5 cm, and 0.2 cm. The lower limit of free fall detection is determined as the value that repeatedly does not allow the detection of a free fall. The logarithmic procedure with the corresponding termination condition is described in the following flow chart (Fig. 13).

```
%Initialize drop height
Drop height = 25 cm;
Position the NB-IoT terminal at h® = drop height;
%Boolean value to initialize the fall result
Free fall = detected;
%Fault variable to move to the next test block
i =1;
%Initial decrement to reduce the drop height
Decrement = 5 cm;
    Do until (i = 6)
        Do until (free fall <> detected)
            Perform the drop test;
            Check whether free fall = detected;
            %Adjustment in the application software
            If (free fall = detected) Then
                Drop height = Drop height - decrement
                Positioning of the NB-IoT end device at new drop height;
            Else
                i = i + 1;
                If (i = 2) Then
                    Decrement = 2 cm;
                Elseif (i = 3) Then
                    Decrement = 1 cm;
                Elseif (i = 4) Then
                    Decrement = 0.5 cm;
                Elseif (i = 5) Then
                    Decrement = 0.2 cm;
                End if
                Drop height = Drop height - Decrement;
                Positioning of the NB-IoT terminal at new drop height;
            End if
        Loop
        free fall = detected; %Boolean value to initialize the fall result
    Loop
```

FIGURE 13. Description of the free-fall measurement test sequence as pseudo-code.

The evaluation of the motion detection (motion state) of the Low Cost Tracker Plus is carried out based on three different case studies so that its suitability for use in situations of different motion intensities can be assessed. The configuration of the Low Cost Tracker Plus, i.e. the sensitivity of the motion detection (in mg) as well as the detection of the beginning and end of motion (in s), are adapted to the respective scenarios in the back-office application before the test begins (Fig. 14).

To enable a comparison of different configurations of the device, and to maintain the required power supply for earch measurement, three Low Cost Tracker Plus with different settings are used simultaneously for the test runs. This means that the energy consumption in the measurements is distributed per device.

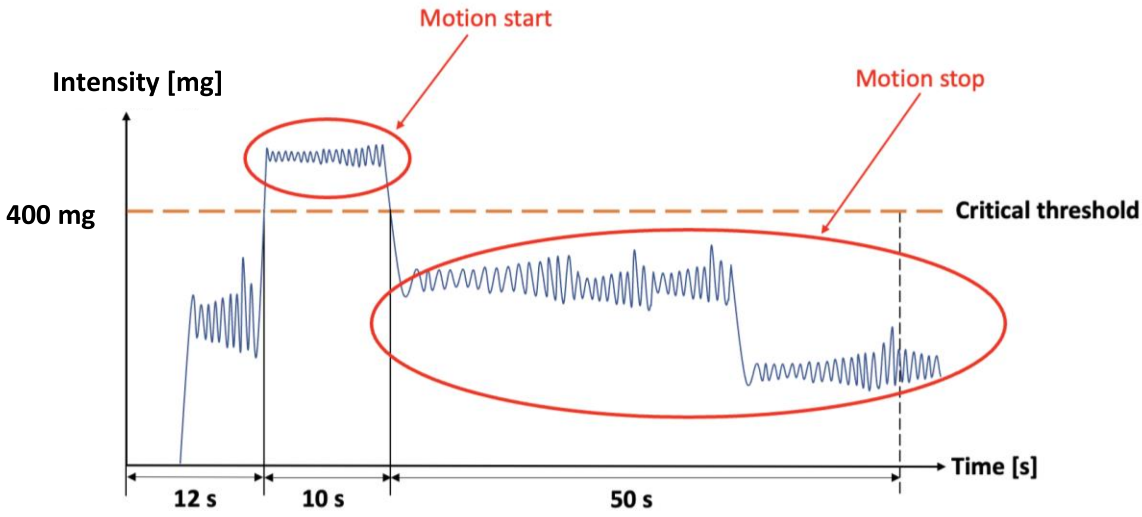


FIGURE 14. Schematic sequence of motion detection.

The use case of low movement intensity (case study 1, Table 6) is simulated by positioning three differently configured Low Cost Tracker Plus in a car parked at the side of the road. In addition, a smartphone is placed in a box with the LCT-Plus. The sensors of the smartphone are used for reference measurement. It is tested to what extent a low intensity of movement, caused for example by passing cars and thus representing noise in the overall view of the movement recording, exceeds a certain threshold value and thus triggers a measurement. The detected value thus serves as the lower threshold value of motion detection, which depicts the car when it is stationary (Fig. 15).

Parameter	Configuration
Sensitivity setting	10 mg – 2000 mg
Time interval movement start	10 s – 1220 s
Time interval movement stop	10 s – 1220 s

TABLE 6. Configuration of the LCT-Plus for case study 1.

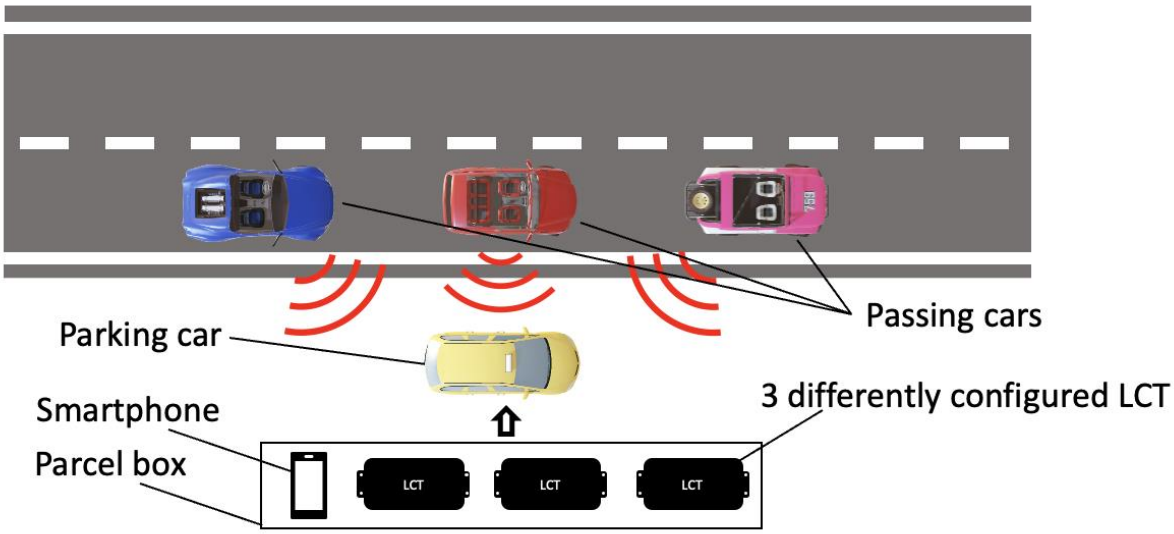


FIGURE 15. Motion sensitivity of the LCT-Plus at the roadside.

To validate the results, the test is then repeated under laboratory conditions. For this purpose, the vibration is simulated with the help of a portal milling machine (Fig. 16). The relevant configurations of the LCT-Plus can be found in Table 7.

Parameter	**Configuration**
Sensitivity setting	10 mg
Time interval movement start	10 s
Time interval movement stop	10 s

TABLE 7. Configuration of the LCT-Plus for laboratory testing.

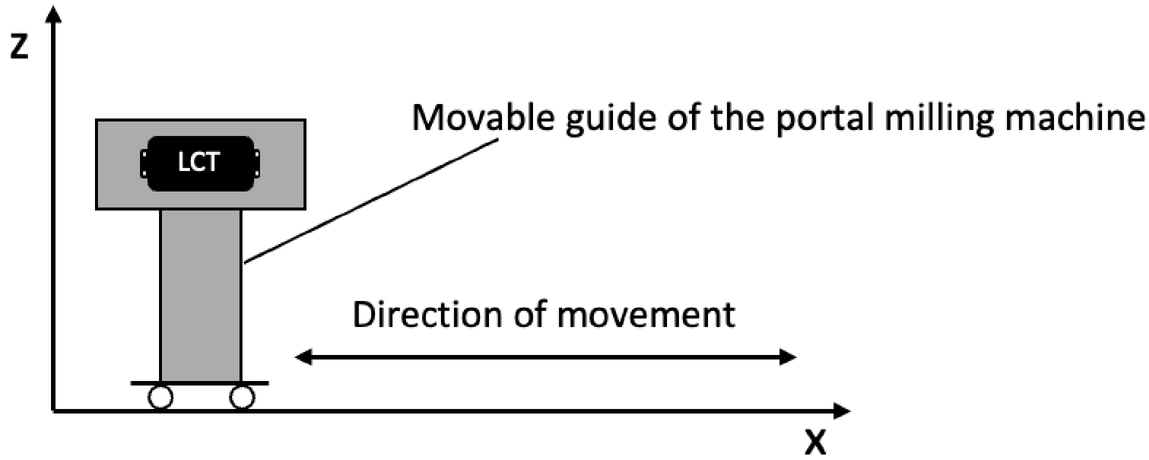


FIGURE 16. Schematic sketch of the experimental setup for motion detection in the laboratory environment.

A medium movement intensity (case study 2, Table 8) corresponds, for example, to the starting and braking of a logistics delivery vehicle. Using the Low Cost Tracker Plus, a message should be triggered when a parcel is delivered. No action should be taken when the vehicle stops for any other reason, such as at a traffic light or similar. To simulate this scenario, the low-cost trackers are positioned in a box inside a test vehicle, and a delivery journey is simulated (Fig. 17).

Parameter	Configuration
Sensitivity setting	400 mg
Time interval movement start	10 s
Time interval movement stop	50 s

TABLE 8. Configuration of the LCT-Plus for case study 2.

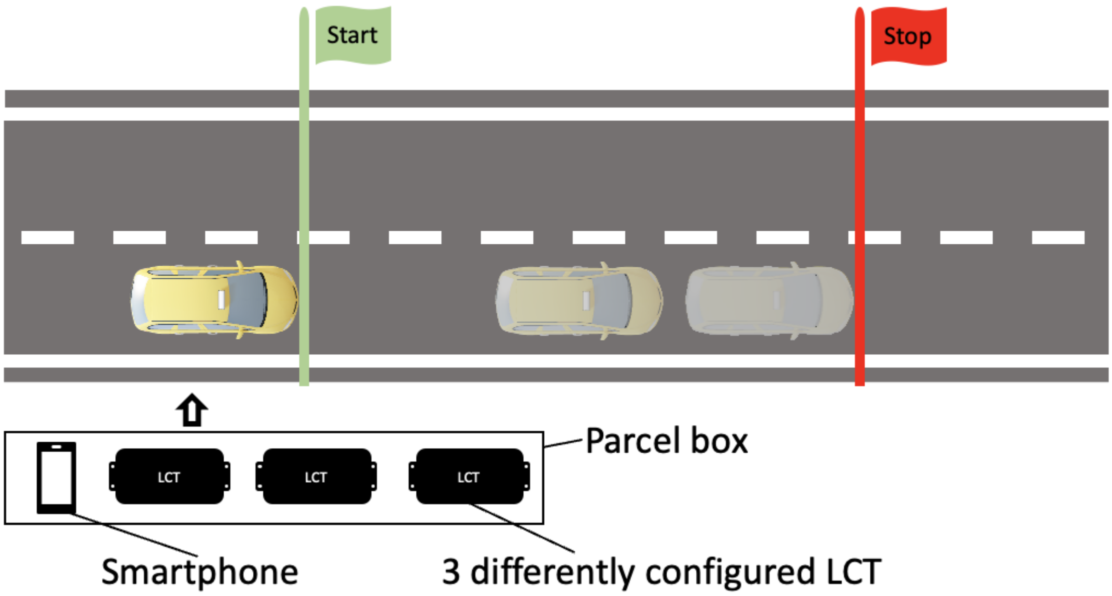


FIGURE 17. Start and stop detection in delivery traffic.

In case study 3, a high intensity of movement (Table 9) is simulated, which corresponds to an abrupt vibration. To test this, the Low Cost Tracker Plus is attached to a pallet. This is subjected to vibrations of varying intensity by deliberately bumping the pallet against a second pallet (Fig. 18). To check the data obtained, a smartphone is attached to the low-cost tracker so that a comparison of the values can provide information about its motion detection performance.

Parameter	Configuration
Sensitivity setting	700 mg
Time interval movement start	10 s
Time interval movement stop	10 s

TABLE 9. Configuration of the LCT-Plus for case study 3.

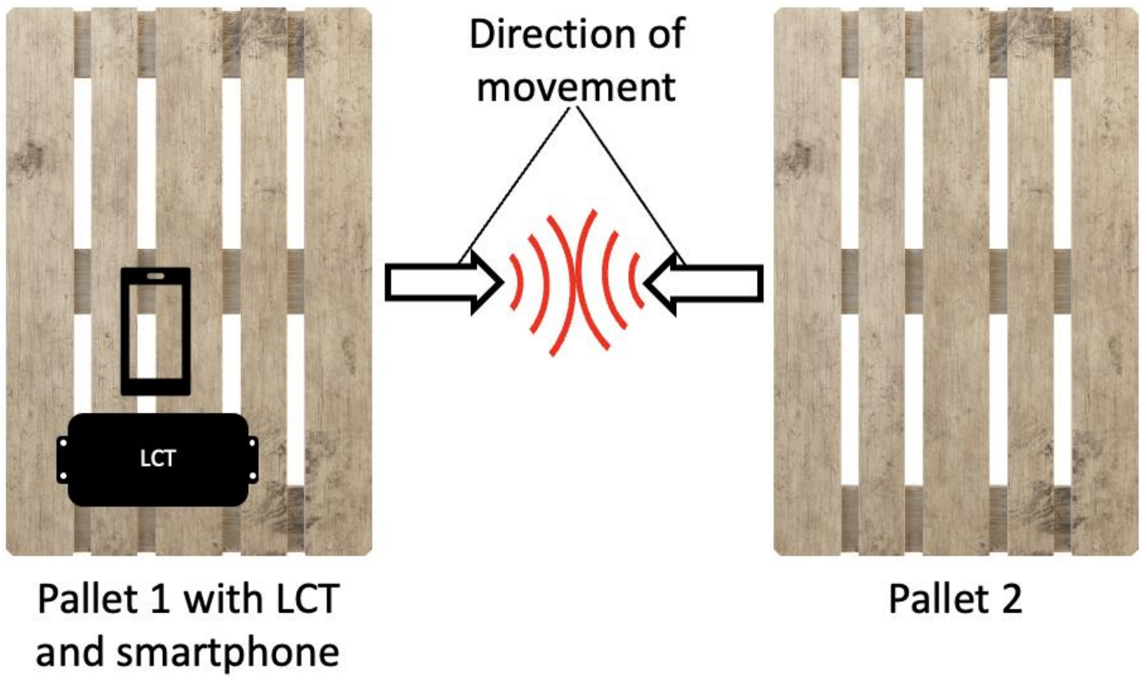


FIGURE 18. Schematic set-up for vibration detection.

3 RESULTS

3.1 ANALYSIS OF THE POSITIONAL ACCURACY

The analysis of the position accuracy is carried out with the help of the determined position deviation between the LCT-Plus and the reference measuring device. Since both systems provide geolocation data (longitude and latitude) as a return value, these are used to determine the distance between the two points. Mathematically, this deviation corresponds to the Euclidean distance between two points (cf. (3), Fig. 19).

$$d^2 = (x_2 - x_1)^2 + (y_2 - y_1)^2 \qquad (3)$$

Since an analytical calculation of the distances between two geolocations requires adjustments due to the curvature of the earth's surface and distance factors for the longitude and latitude lines, the position deviations are traced using Google Maps and verified by our calculations and comparisons with other common online tools.

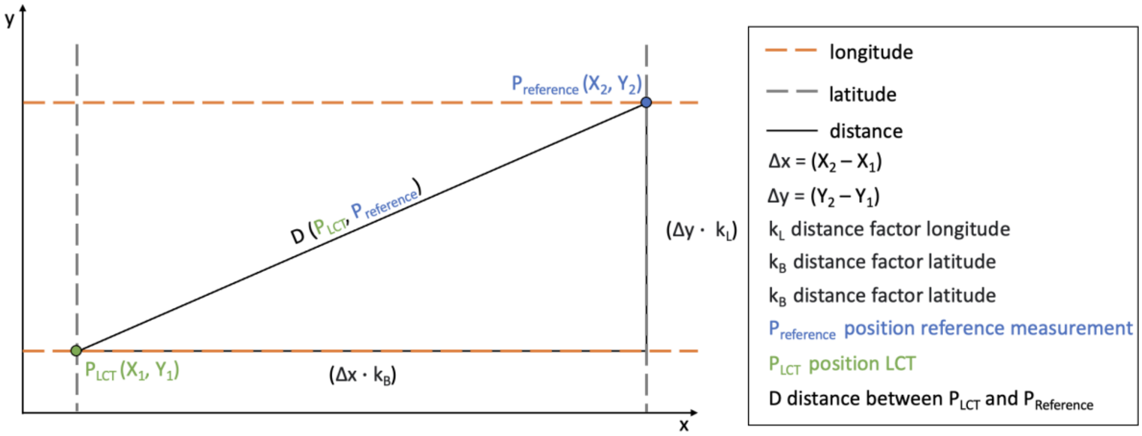


FIGURE 19. Calculation of the Euclidean distance between two points.

The general deviations between LCT-Plus and reference measurements are shown in Table 10. Here the mean position deviations are listed regarding the factors defined in Table 4.

Measuring point	Average deviation of LCT-Plus
Total measuring points	238,57 m
Urban	55,06 m
Rural	375,08 m
4G	248,90 m
2G	238,57 m
No forest	84,23 m
Near forest	358,49 m
Forest	382,64 m
No buildings	433,03 m
Very few buildings	56,33 m
Few buildings	51,82 m
Many buildings	60,73 m
No lake	287,52 m
Close to the lake	34,99 m
Directly at the lake	67,13 m

TABLE 10. Comparison of the positional accuracy of the LCT-Plus and reference measuring device concerning defined factors.

When looking at the average deviations regarding the defined factors, it can be noted that measurement in an urban environment has a higher accuracy than in a rural environment. This may be related to the possibility of determining the position via WLAN, since surrounding MAC addresses can be used by the LCT-Plus to determine the position.
Furthermore, cellular mobile radio technology does not have a significant effect on the measurement result regarding position accuracy.

A significant difference in terms of positional accuracy can be observed in the evaluation of the factor "nature". The assumption is that the factor level "no forest" coincides with a position measurement within an urban environment, whereby a higher accuracy can be achieved. The other two factor levels are usually found in rural environments, which is why a higher position deviation seems plausible here as well.

The positional accuracy of the "buildings" factor is analogous to that of the "nature" factor. The factor level "no buildings" is found in rural areas, which tend to provide less accurate values regarding geolocation.

The evaluation of the factor level "many buildings" compared to the other two factor levels is interesting. Even if the inaccuracy of the measured position is only marginally higher, the surrounding buildings are an indicator of additional shielding or interference effects that cause this inaccuracy.

The factor "lake" shows that the level "close to the lake" provides the best accuracy values. Here, too, it can be assumed that the urban influence plays a significant role in the low position deviation.

For a more detailed examination of the measured position accuracies of the LCT-Plus, the derived absolute deviations are broken down regarding the underlying network coverage and the previously defined influencing factors. To estimate the possible influence of the existing network coverage, the deviations of the respective factor levels are evaluated.
The results show that higher position accuracy can be achieved by the investigated system when the LCT-Plus transmits the position in more urban areas. Furthermore, in urban areas, 2G network coverage has a higher position accuracy. In rural areas, accurate positioning is also possible using LCT-Plus even though there is no network coverage (Fig. 20).

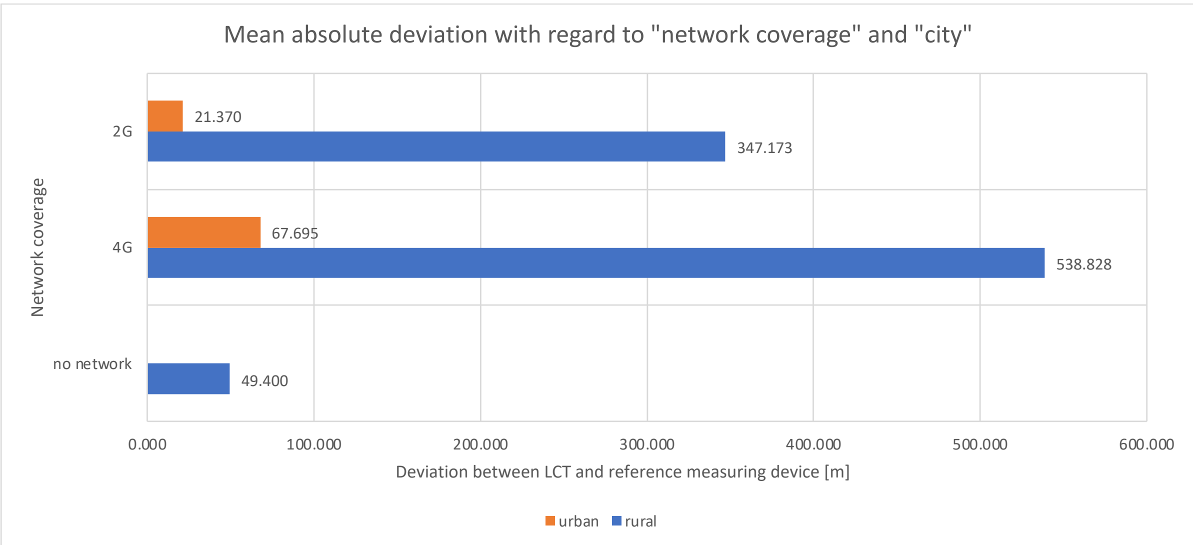


FIGURE 20. Mean absolute deviation regarding “network coverage” and “city”.

In the case that the LCT-Plus transmits from forest areas, a clear influence by nature can be seen. The position transmission from forest areas or areas close to forests constantly shows a higher mean absolute deviation compared to the reference measurements.

Compared to the measurements in urban environments, there are significantly higher inaccuracies regarding the location positions with 2G network coverage. Both the 4G network coverage and the measurement positions without network coverage again show small position deviations for the configuration "no forest" on average (Fig. 21).

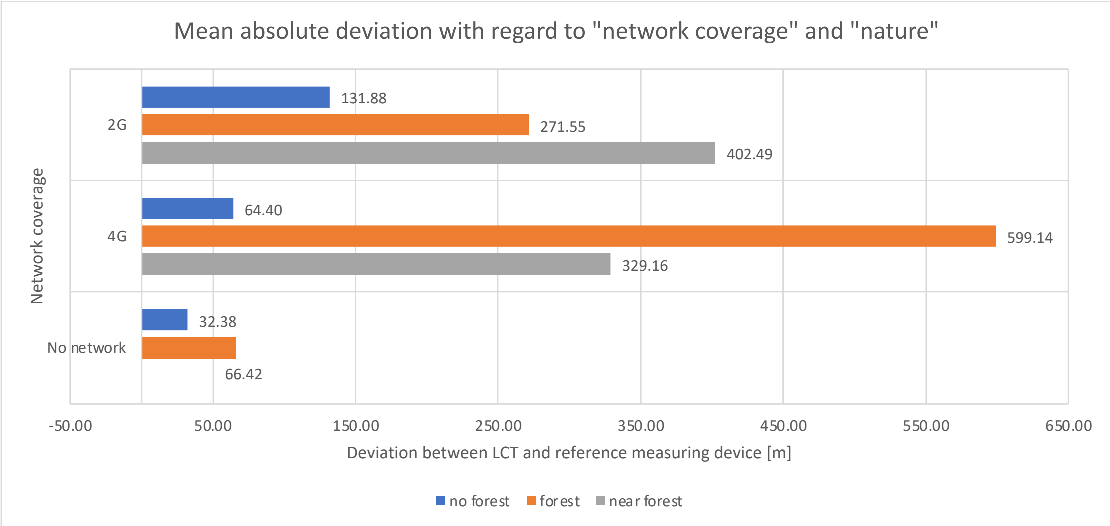


FIGURE 21. Mean absolute deviation regarding "network coverage" and "nature".

In general the influence of surrounding buildings at the respective measurement points is relatively low. Once again it can be seen that measurement points without network coverage have a high accuracy and that these measurement points only occur where no or few building influences appear. The high mean absolute position deviations for the measurement series carried out at points with low building density are striking. Regardless of the network coverage, a high building density leads to more accurate position information from the LCT-Plus (Fig. 22).

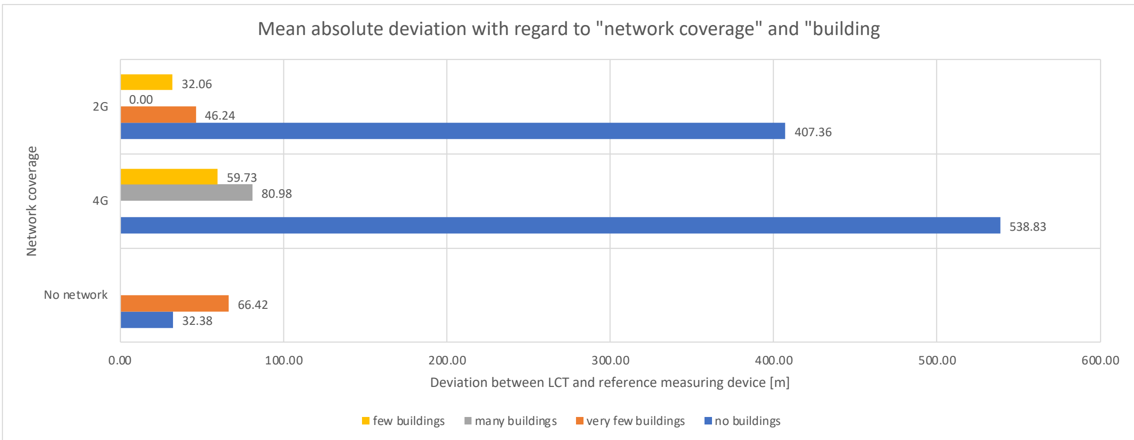


FIGURE 22. Mean absolute deviation regarding "network coverage" and "building".

The results from the measurement points of the influencing factor "lake" show that the inaccuracies for 4G network coverage are again higher than the comparative measurements for the factor level "no lake". As with the influencing factor "building", it can be seen that the proximity to the lake has no significant influence on the position accuracy (Fig. 23).

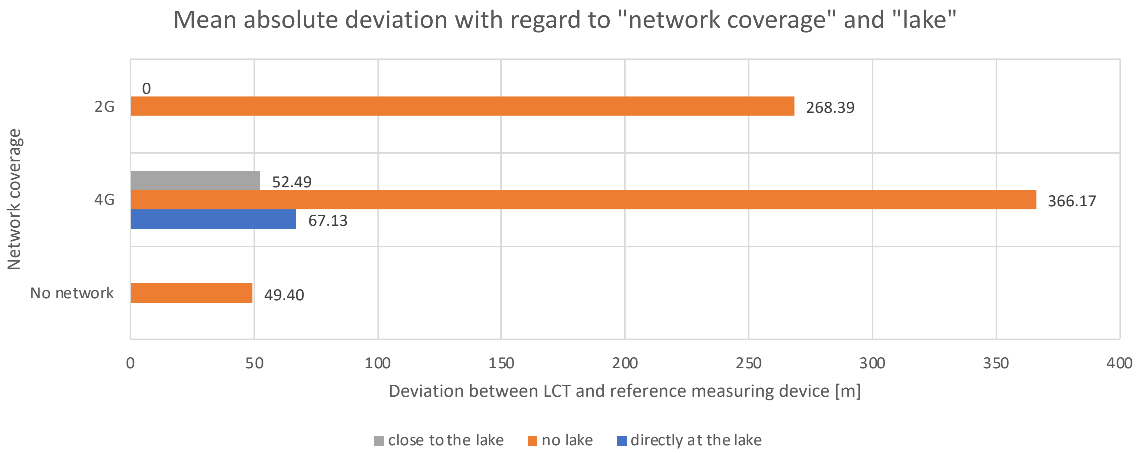


FIGURE 23. Mean absolute deviation regarding "network coverage" and "lake".

3.2 ANALYSIS OF THE TEMPERATURE

To check the measurement accuracy of the temperature sensor, the deviation between the reference measuring device and the LCT-Plus is determined for each measuring point to subsequently calculate the average deviation within a measuring point range (α, β, γ, δ). The measurements of the respective areas are averaged together as they are in a similar geographical location. The average total deviation determined from these values is -0.48 °C (Table 11).

Area of measurement	Ø Temperature deviation
Alpha	-0.50 °C
Beta	-0.44 °C
Gamma	-0.56 °C
Delta	-0.42 °C
Ø Total deviation	-0,48 °C

TABLE 11. Measuring accuracy of the temperature sensor.

The overall analysis of the recorded temperature readings and the derived deviations from the reference measurements is visualized in Fig. 24 and Fig. 25 and shows that the LCT-Plus achieves high accuracy.

However, there is a systematic error as 23 of the recorded 27 measurements show a negative temperature deviation compared to the reference measurements. The total deviation across all measurements results in a mean value of $\Delta\bar{\vartheta}$=-0.43 °C with a standard deviation of σ=+/-0.42 °C.

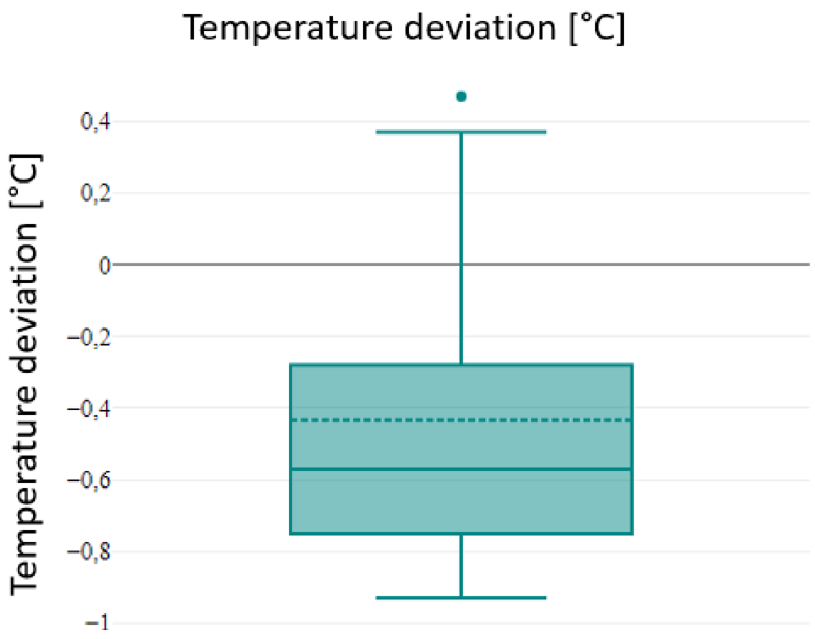


FIGURE 24. Boxplot of the temperature deviation of the LCT-Plus.

3.3 ANALYSIS OF THE FREE FALL DETECTION

The test to determine the lowest drop height that allows the Low Cost Tracker Plus to detect a free fall results in a lower limit of 6.6 cm (Table 12). If the device has detected a free fall, a discrete signal is sent to the IoT platform, and the dashboard displays the message of a vibration or the detection of a free fall.

Point	Corresponding fall height of the LCT-Plus	Free fall detection
P1	25 cm	√ (Yes)
P2	20 cm	√ (Yes)
P3	15 cm	√ (Yes)
P4	10 cm	√ (Yes)
P5	5 cm	X (No)
P6	8 cm	√ (Yes)
P7	6 cm	X (No)
P8	7 cm	√ (Yes)
P9	6,5 cm	X (No)
P10	6,8 cm	√ (Yes)
P11	6,6 cm	√ (Yes)

TABLE 12. Measurement result of the free fall detection.

3.4 ANALYSIS OF THE MOTION DETECTION

The analysis of motion detection aims at evaluating the system's ability to reliably detect motion. For this purpose, three different case studies are analyzed, which are characterized by a high, a medium, and a low sensitivity level of motion detection. These three different case studies aim to support the interpretation of the suitability of the LCT-Plus in different transport logistics scenarios.

The test results from case study 1 (high sensitivity level) show the detection of an acceleration of 10 mg when exceeding a movement duration (movement start) of 10 s without exception. This means that the use case of vibration detection by passing cars is detected reliably. Use case 2 (medium sensitivity level) simulates the delivery of consignments by a delivery vehicle. A characteristic of parcel delivery in the last mile of transport logistics is the high number of starts and stops of the delivery vehicle. The movement start of 10 s and the movement stop of 50 s determine the configurations regarding the time durations from which a respective change in the movement state is to be detected. The comparative value of the acceleration in this application is 400 mg. Table 13 and Table 14 summarize the measurement records and support a very accurate detection of the movement mode.

Acceleration [mg]	Triggering of the motion
345	X (No)
171	X (No)
83	X (No)
412	√ (Yes)
463	√ (Yes)
390	X (No)
272	X (No)
198	X (No)
306	X (No)

TABLE 13. Measurement result of motion detection based on acceleration (use case 2).

Motion stop [s]	Triggering of the motion
65	√ (Yes)
58	√ (Yes)
55	√ (Yes)
52	√ (Yes)
50	√ (Yes)
49	X (No)
45	X (No)
70	√ (Yes)
80	√ (Yes)

TABLE 14. Measurement result of the motion detection based on the time of the motion stop (use case 2).

The final application case investigated for motion detection aims to detect a shock vibration of a load carrier to conclude possible damage to the load (application case 3). A threshold value of 700 mg for the acceleration and a time interval of 10 s for the movement start and stop are configured. Table 15 summarizes the results of the measurement series and shows that only in one case the impact of a pallet on the floor is not reliably detected.

All acceleration values are compared using the sensors of a smartphone and the Phyphox application [43]. Fig. 25 visualizes the percentage frequency of all detected movements and indicates a very reliable result within the investigation horizon concerning movement detection by the LCT-Plus.

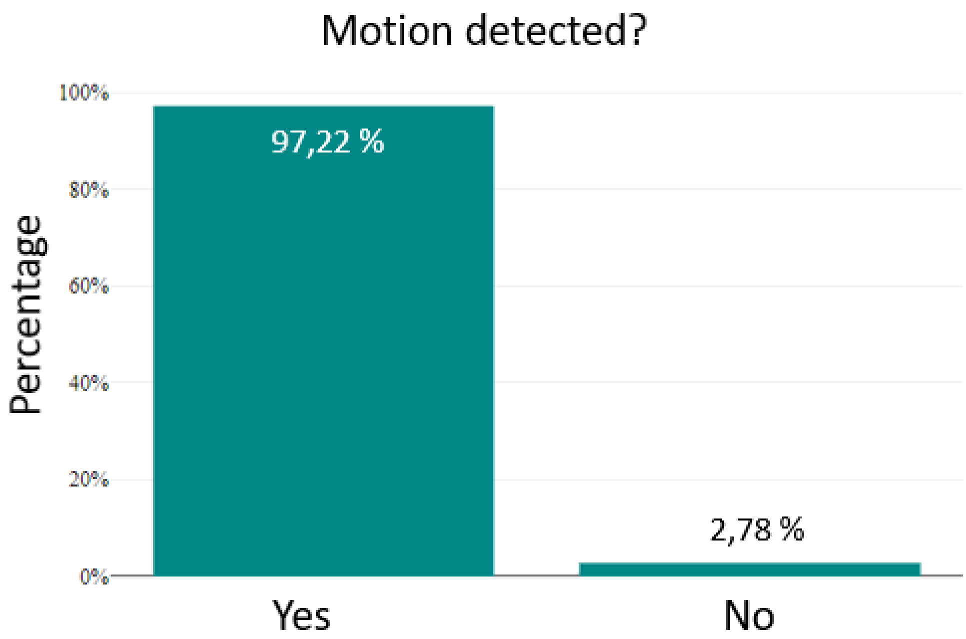


FIGURE 25. Analysis of the relative frequency of movement detections.

4 DISCUSSIONS & IMPLICATIONS

In this section, the results of the present study are discussed and their implications for the application of the investigated NB-IoT system within transport logistics are highlighted. The investigated metrics are considered as crucial parameters for the performance and applicability of the NB-IoT system in the underlying domain. In the following, the most important results are compared to the expected specifications (Table 15), and their impact on the use of the LCT-Plus is discussed.

4.1 DISCUSSIONS AND IMPLICATIONS OF POSITION MEASUREMENT

In terms of positional accuracy, the LCT-Plus technical specifications state accuracies of up to 50 m in urban areas and up to 300 m in rural areas. However, the tests showed an average deviation of 55.06 m in urban areas and measurement accuracy of 375.08 m in rural areas.

The accuracy of localization using low-cost trackers depends on the surroundings of the measuring point. The results show a clear tendency towards more accurate positioning when the LCT-Plus is located near buildings. During our exchange with the hardware supplier, they kindly provided a potential explanation for this observation. It seems that the LCT-Plus device is capable of localizing through passive detection and analysis of WLAN signals, without requiring Wi-Fi network connectivity. This method involves scanning and measuring the strength of RSSI signals from surrounding access points, which are detectable even without password-based authentication. The device uses triangulation or multilateration techniques based on signal strength measurements to estimate its position. We hope this information is helpful to you. Additionally, to further improve accuracy, it can reference a database of known Wi-Fi access point locations. This method can be particularly helpful in urban areas with high-density Wi-Fi networks, offering a practical solution for location determination in situations where GPS signals may be unreliable or unavailable. It can also be useful when direct Wi-Fi network connection is not possible due to security or technical limitations.

The deviation of the actual position from the determined position in rural areas shows that the technology is not suitable for applications with high accuracy requirements (Table 15). These accuracy requirements are assumed, for example, in asset tracking of A-goods with out-of-town transshipment points.

In the urban area, the collection of location data with the observed position accuracy is sufficiently accurate for applications such as point monitoring within transport logistics (Table 15).

However, since the energy requirement of the device increases with an increase in the transmission frequency, the device is not suitable for the monitoring of delivery vehicles, as is required, for example, in the transport logistics last mile in the area of city logistics. On the other hand, the technology is suitable for longer routes and longer transmission intervals, such as the tracking of lorries, as the reduced transmission frequency reduces the energy requirement accordingly.

Measured parameters	Expected deviations	Measured deviations
Position accuracy	Urban: approx. 50 m Rural: approx. 300 m	Urban: approx. 55,06 m Rural: approx. 375,08 m
Temperature	+/- 0,2 °C	- 0,43 °C
Motion detection	No deviation from the configuration in the dashboard	Max. +27,53 mg (0,27 m/s^2) Excess of the duration of the movement start/-stop: 0 s
Free fall detection	Detection from a height of min. 10 cm	Detection from a height of min. 6.6 cm

TABLE 15. Comparison of the expected deviations with the measured deviations of the LCT-Plus.

4.2 DISCUSSION AND IMPLICATIONS OF TEMPERATURE MEASUREMENT

According to the manufacturer, the temperature sensor enables temperature measurement with an accuracy of +/- 0.2 °C. The average deviation was determined by the test. However, a mean deviation of - 0.43 °C was determined in the test. Furthermore, a standard deviation of +/- 0.42 °C results in the analyzed series of measurements. This range of validity of the observed measured values shows that the temperature can only be measured with insufficient accuracy for high requirements.

The measured temperature is indicated as an integer so that the LCT-Plus is only suitable for temperature measurements with low accuracy requirements. Furthermore, it requires an acclimatization time of 15 minutes to provide unbiased results.

The strengths of the LCT-Plus lie in the recording of the measured values, which is guaranteed even without network reception, and the transmission of the values, which functions reliably even with poor signal strength.

The detection of temperature deviations in the range of +/- 0.5 °C [44] required for monitoring some fruits and vegetables can only be insufficiently fulfilled by the LCT-Plus due to the proven achievable accuracies. However, condition monitoring of temperature-uncritical goods using the LCT-Plus is certainly possible and offers transporters a cost-effective and sufficiently reliable alternative to other systems.

4.3 DISCUSSION AND IMPLICATIONS OF FREE FALL DETECTION

In addition to monitoring the position and temperature of the load, the LCT-Plus ensures the motion detection of a moving object through the embedded accelerometer. The requirements for the LCT-Plus regarding the reliable and error-free detection of the state of motion are confirmed by the various case studies.

According to the LCT-Plus manufacturer, the minimum height required to detect a free fall is 10 cm. However, the tests carried out have demonstrated reliable registration of a free fall at a lower minimum height of 6.6 cm. Due to the existing accuracy in the detection of a free fall, reliable detection and documentation of vibrations in the loading process and the course of the journey can be guaranteed. This provides the transporters with more transparent traceability of possible damage and offers a basis for safeguarding responsibilities in the event of damage.

4.4 DISCUSSION AND IMPLICATIONS OF MOTION DETECTION

In addition to the detection of a free fall, the LCT-Plus can also detect a multi-axial general movement. The LCT-Plus reliably detects movement for all three applications.
The first use case of motion detection describes the detection of vibrations caused by passing vehicles. This use case ensures that a lower limit can be determined to be able to comprehend such noise in an overall interpretation of the movement and to understand that a load or vehicle is stationary.

The second use case enables the differentiation of a drive phase from a stop phase within a parcel delivery process. Thus, by analyzing the second use case, it is possible to track the journey of the vehicle based on motion detection.

The third use case of movement detection is the impact of a load and can provide information about possible damage. This movement can also be reliably detected by the LCT-Plus and, in combination with the other status information, can help transporters to clarify possible cases of damage.

4.5 LIMITATIONS

To embed the results of the study in the research context, it is important to consider the limitations of the research undertaken within this study.
A significant limitation of these results is the observation horizon, as the investigations only refer to the greater Friedrichshafen area on the southern German side of Lake Constance. Although this area is suitable for carrying out the tests due to the diverse geographical situation and the resulting heterogeneous network coverage, it makes sense to look at other locations to validate the results.

Furthermore, the measured values suggest that a closer look at the network coverage allows for more profound meaningfulness and interpretation of the measured values. The information regarding network coverage is provided by the country's largest network provider but needs to be validated and possibly enriched by information from other providers and corresponding authorities.
Regarding the evaluation of the generated data, the lack of access to the sensors installed in the device and thus to the raw data collected by the LCT-Plus is a limiting factor, in terms of the interpretation of the results within this study. To be able to assess the accuracy of the measurements nevertheless, corresponding reference measurements were carried out.

Since the three LCT-Plus used have different configurations regarding sensitivity in vibration measurement (application case 1 of motion detection) with discrete distances to each other, the exact configuration for motion detection must be determined by employing an iterative approximation procedure using a more extensive series of measurements. Such a systematic procedure makes it possible to determine the lowest sensitivity value at which motion is detected by the terminal. An analogous procedure is also proposed for the other use cases of motion detection since no extensive measurement campaign was carried out within a preliminary investigation to isolate interfering influences and thus better control the measurements.

Furthermore, no extensive reference measurements were undertaken for the measured variables "free-fall detection" and "motion detection" that could be used as a basis for interpreting the measured deviations.

Another limiting factor of this work is the experimental setup. To be able to make more reliable statements for transport logistics, the system under investigation must be used in real trucks. This was not initially undertaken in this study, as the focus was on the basic system evaluation.

5 CONCLUSION

Within the scope of the investigations, it was shown based on three different case studies that NB-IoT end devices such as the Low Cost Tracker Plus are fundamentally suitable for monitoring transport logistics processes. The reliability of the measurement of relevant parameters was used as a criterion for assessing suitability regarding a specific application scenario. The limitations discussed the suitability for certain application scenarios are not due to the NB-IoT connectivity technology, but result from other use case-specific aspects, such as the energy requirements of the device associated with a high transmission frequency or special requirements regarding the measurement accuracy of temperature deviations.

The advantages of NB-IoT in terms of penetration indicate that the investigated system is not limited to the use case of cargo tracking within the transport process. Another application is the tracking of swap bodies and load carriers within intra- and yard logistics, as NB-IoT ensures building penetration.

Furthermore, the terminal under investigation has Bluetooth Low Energy (BLE) radio technology, which extends the system's range of applications to data communication and goods tracking within warehouses. A necessary system landscape is realized by installing corresponding beacons to ensure data communication of the LCT-Plus on BLE.

In addition to the load tracking and condition monitoring options, the system can be used to set up a geofence to transmit automated signals when the LCT-Plus leaves the defined area of operation.

In summary, LCT-Plus is suitable for a variety of use cases within the transport logistics environment and is a good way to increase visibility and transparency regarding cargo and mobile objects.

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Evaluation of a Narrowband-IoT system in the transport logistics application field

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