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THE USE OF LORA TECHNOLOGY AS AN ALTERNATIVE TO GPS IN THE NAVIGATION OF A MOUNTAIN VEHICLE INTENDED FOR PEOPLE WITH SPECIAL NEEDS

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Abstract:

The navigation system for such a vehicle may use hardware solutions that differ in price, functionality, user-friendliness and problems associated with their operation. The navigation of such an off-road vehicle may be based on: GPS, LoRa wireless communication, and IMU inertial units. However, as the first half of 2024 has shown, this system is experiencing significant disruptions. In extreme situations, it may even be disabled (e.g. because of warfare). Where special-purpose off-road vehicles for PWSN are operated in mountainous terrain, especially on rocky ground with various structures, IMUs are particularly susceptible to errors building up during travel. This article addresses the research on the LoRa technology envisaged for implementation in a navigation system intended for this type of vehicle. Given the foregoing premises, it is crucial to determine the possibility of effective exchange of information in the transmitter-receiver system using the LoRa protocol for purposes of communication in difficult mountainous terrain, in the presence of obstacles, and often under harsh weather conditions. The pilot studies discussed in this article were conducted with the above problems in mind. This article formulates assumptions for a navigation system based on the LoRa standard. Based on the studies conducted by the authors, both the implementation validity as well as the advantages and disadvantages of the solution proposed have been described. The research results imply that the solution in question can be treated as an alternative if the GPS signal is either unavailable or significantly disturbed, and its additional features provide significant support for PWSN using off-road vehicles.

Keywords: *LoRa, GPS, IMU, MTB, people with special needs, trip planners*

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1. Introduction

The special-purpose off-road vehicle designed for mountain tourism, engineered and built under the project in question, is intended for navigating in difficult terrain, mainly on mountain trails. Its specifics make it an off-road vehicle. Therefore, it can be used to negotiate difficult terrain, off the paths designated for travelling. Because of these characteristics, the capacity to establish the vehicle's location proves to be an important aspect. Such functionality of this special-purpose vehicle makes it possible to increase the driver's safety, and on top of that, it facilitates the organisation of traffic on mountain trails as well as in other kinds of terrain suitable for tourism (Park et al., 2022; Clery et al., 2017; Ehnstrom, 2022; Sundling et al., 2024; Krevs et al., 2023; Urbański, 2018; Garcia et al., 2022). It is also for the vehicle's positioning capability that one can better manage the limited space of national parks and mountain areas (Prato, 2001; Park et al., 2022; Zhang et al., 2017). One can particularly speak of limited tourist capacity regarding high mountains, where there is generally much less space available to tourists. The problem of limited accessibility is relevant for some of the most popular tourist attractions, where the capacity in question has been exhausted for a long time, such as the Acropolis in Athens, the Himalayas, or the Tatra Mountains in Poland (Dutka, 2022; Apollo, 2017). Tourist accessibility can be controlled using diverse systems for navigation, organisation, and management of the transfers made by tourists. For this reason, there is a problem of positioning of specific objects in areas of tourism, including mountain areas, which requires research enabling adequate solutions to be found. Moreover, this problem can only be expected to grow as international and regional tourism continues to develop (Benckendorff et al., 2017; Ding, 2016; Nyasha et al., 2020). Various tourist traffic management and support systems, such as the GPS or access control systems based on electronic access cards, offer diverse solutions to the issue at hand. There are several strictly technical challenges, such as locating the points to cover the area of interest and spacing them out to accommodate the tourist population. Some mountain trails are crowded, while others are not (authors' materials not yet published: Staniek, M., Celiński, I., Modelling of mountain tourism related transfers of persons with disabilities by means of a special-purpose off-road vehicle).

The navigation system on board a special-purpose off-road vehicle intended for people with special needs (PwSN) can make use of different system solutions, varying in terms of price, functionality, user-friendliness, or resistance to interferences (intentional and natural). However, there are also specific problems which arise from the choice of a navigation system assumed for operation under conditions. The navigation system of a special-purpose off-road vehicle for PwSN can be based on systems such as the GPS, diverse wireless communication solutions, inertial measurement units (IMU), and many other techniques, including visual. Because of its availability, simplicity of operation, as well as the range of matching software and signal receiving equipment available, the GPS is currently by far the most popular system (Savchuk et al., 2015; Shoval et al., 2014; Sinha, 2017). However, as evidenced by the ongoing armed conflict in 2023 and 2024, this system is also not completely resilient to disruptions. In extreme situations, it can be deliberately disrupted or disabled (e.g. during warfare) (Elmahdy et al., 2009; Schmidt et al., 2020; Mulugeta et al., 2022; Cyberdefence24, 2024; Grier 1996; Westbrook, 2019). In the event of disruptions, its advantages over other solutions (e.g. positioning accuracy, universality) dwindle dramatically. IMUs also have an established position in the domain of navigation systems (Zhao, 2011; Keeper et al., 2018; Yi-han et al., 2023). Considering the requirements of the operation of a special-purpose off-road vehicle intended to be used by PwSN in mountainous terrain, especially on rocky ground of non-uniform surface structure, the inertial systems are particularly susceptible to error build-up during travel (due to surface-induced vibrations). They are also prone to interference from various sources, such as temperature changes or electromagnetic factors. Additionally, IMUs require time-consuming and complex calibration. About the foregoing, this paper addresses studies of the LoRa technology, used to establish the navigation capabilities for this type of special-purpose vehicle, pertaining to navigation based on measurement of the vehicle orientation against reference points in a transmitter-receiver system. Such a solution is envisaged to provide support for PwSN travelling by means of special-purpose vehicles in mountainous terrain. The LoRa technology is designed for long-distance license-free band communication, but it can also be used for navigation purposes (Noreen et al., 2017; Talla et al., 2017; Sinha et al., 2017; Kietzman et al. 2024; Kolobe et al., 2021; Fargas et al., 2017; Augustin et al, 2016). However, in the context of its application discussed in this paper, the measures most frequently used comprise identification of external infrastructure (non-GPS, e.g. GSM) based on popular positioning methods, e.g. triangulation. The approach presented in this article is not about high-precision positioning of the special-purpose vehicle for PwSN. The crux of the navigation system proposed is the possibility of determining an approximate position in the absence of any supporting infrastructure, apart from the system in question, and without any advanced visual systems. The latter are currently rather costly and often unreliable in mountain conditions. The authors believe that trouble-free movement in mountainous terrain is possible if one navigates against reference points based on the LoRa system components. Examples of the reference point-based navigation are provided in numerous publications (Kuo et al., 2020; Zhang et al., 2016; Latif et al., 2024; Ohtsu, 2015; Dietze et al., 2005; Deng et al., 2011; Yu et all, 2010; Bachras et al., 2019). The relevant technical issues, as well as their solutions, as described in the literature on the subject, are mainly related to navigation using a variety of visual and augmented reality systems. The approach discussed in this paper is different, as it relies on radio communication.

LoRa studies can be divided into theoretical and experimental. This approach allows for the evaluation of LoRa's theoretical and empirical performance. In the former, numerical models and other domain-specific software are used to explain the theoretical communication capabilities of this technology. This type of research confirms the consistency of theoretical and numerical results for various coding schemes, such as Hamming. This is assessed, for example, in terms of signal-to-noise ratio (SNR). Empirical studies involve experimental configurations using commercially available LoRa hardware. This aims to demonstrate the feasibility of the technology under study. This approach, firstly, enables the study of the impact of various parameters on the packet error rate (PER). Practical analysis confirms the consistency between theoretical and measured noise levels and can confirm the strength of the influence of observed parameters, for example, on the system's PER.

2. Research problem and methodology

Purpose of the research is to verify whether it is possible to use the LoRa radio communication system in the navigation of off-road vehicles in the mountains. On the one hand, such navigation seems to be designed for mountainous areas, providing coverage of large areas, but on the other hand, certain specific terrain features make it a research challenge. Here we have significant point-to-point coverage not only horizontally but also vertically. This creates very interesting transmission combinations not found in flat terrain. Therefore, although the goal seems obvious, its implementation is not necessarily. The claim that the use of LORA is feasible will be proven below using a few empirical examples. The general objective is developed into a few specific objectives for different system configurations. In the context of this thesis, the problems with the network's throughput and transmission time are also not obvious. This parameter is particularly controversial from the perspective of emergency situations, which would require a change to the transmission time. At this stage, we have not yet investigated this issue.

Regarding the problem analysed in this paper, what proves crucial for trouble-free navigation of a special-purpose vehicle intended for PwSN in mountainous terrain is determining the possibility of effective information exchange in a transmitter-receiver system. It is planned that special-purpose vehicles for PwSN will be equipped with such devices, all communicating via the LoRa protocol. When performed in difficult mountainous terrain, namely with significant differences in elevation, in heavily winding roads, with different spatial configurations of the transmitter-receiver system, with the presence of obstacles, and often in difficult weather conditions, such communication appears to be problematic. Hence the pilot studies described in this article. It should be noted that the GPS is not fundamentally a two-way system. It basically performs no function other than positioning. The LoRa protocol-based system is intended by the authors to offer additional features, besides the navigation itself, considered useful to PwSN. For example, it can be used by the Mountain Volunteer Search and Rescue service (GOPR) as a part of a mountain rescue system.

The term LoRa (Long Range) describes a long-range wireless communication protocol and system, used with limited power expenditure. Its main purpose is communication (more distant, rather than close-range) between IoT (Internet of Things) devices (Sornin et al., 2015; Ferran et al., 2017). The distances between devices communicating in the LoRa system come to several kilometres (0–10). However, according to the descriptions provided in the literature, the effective LoRa communication range varies to a considerable extent. There is abundance of available data on the communication distances successfully achieved, ranging from a few to hundreds or even thousands of kilometres. It's worth emphasizing that ranges, in addition to terrain, infrastructure, and development, also depend on other conditions, including the system setup. This system, in turn, depends on local legal regulations. This, in practice, means that actual ranges are significantly lower than those declared by the system manufacturer. We managed to achieve a range of up to 2.5 km in built-up areas, which is the lower limit of applicability. The solution's long range and low power consumption are associated with low data transmission rates, ranging between 0.x kb/s and 30.0 kb/s. This is the main reason why the LoRa protocol is generally not used for popular real-time telecommunications services. This is also due to its considerable transmission latency (Zulfiqar et al., 2023; Rydell et al., 2022). Latency in a LoRaWAN network comprising several hundred devices can be up to 1–2 seconds, but typically the average is much lower, barely exceeding 200 ms. LoRa is a radio communication network using modulation with what is referred to as chirp spread spectrum (CSS) (Edinio et al., 2023; Springer et al., 2000). It is a proven technology of a several decade-long track record.

However, in the context of the subject matter of this article, there are problems related to the communication using this standard. The advertised long range is only feasible in open space, while it declines considerably in built-up urban environment or under other unfavourable conditions. The large communication coverage can also be conditioned by national (legal) regulations. For example, such a condition is a maximum of 1% of transmission time, which means that, given the demanding transmission parameters, only one message can be transmitted per minute. Moreover, the system is susceptible to various interferences, including those related to weather conditions. Studies of the overall body of problems related to the impact of weather conditions on the LoRa technology have been relatively well documented. The system range depends on the specifics of the urban area, the layout of buildings, the material from which they are made, the terrain relief, and the mining heritage (e.g. presence of mining spoil heaps which can emit trace radiation). Many researchers, following their in-house observations, limit the effective LoRa coverage to distances ranging from a few hundred metres to 2–3 km in open terrain, and to a few dozen metres in buildings (Augustin et al., 2016; Petajajarvi et al., 2015; Zhang et al., 2020). It should be noted that, in buildings, the LoRa signal propagation is still better than that of other wireless networks (Zhang et. al., 2020). It is a communication system which requires thorough examination of its local context under different operating conditions. Nevertheless, it can be taken into consideration in terms of specific needs, such as those presented in this article against the use of special-purpose vehicles for PwSN. According to our observations, most problems appear in terrain with close elevations combined with a large winding road, it is more of a loess soils than a mountainous terrain.

Weather conditions, as aforementioned, are also of great importance for radio communication. In the LoRa context, the following factors are studied: effect of device temperature, ambient temperature, relative humidity, solar radiation, or effect of massive precipitation (in subtropics) (Olakunle et al., 2021; Boano et al., 2018; Bezerra et al., 2019; Al-samman et al., 2020; Kumar et al., 2010; Marzuki et al., 2009). These adverse operating conditions are very often associated with a specific type of land development. Humidity and rainfall have different effects on urban areas and different ones on forested land (Al-Saman et. al., 2020). Similar can be said about the conditions of exposure to solar radiation (Ferriera et al., 2020). What one can also frequently observe is a combined effect of various factors on transmission quality. Where the navigation system is used in the mountains, factors such as terrain relief, weather conditions and, for example, specific mineral deposits located nearby which may affect the signals of vehicle on-board systems (e.g. uranium deposits) are considered crucial. Atmospheric conditions, such as heavy rain and snow fall, especially with water and snow accumulation on a mountain trail, are often the critical factor in terms of the impact on transmission conditions (Blazejczyk, 2019). The trail profile matters itself, but also elevation differences or the curvature of paths.

Reference point-based navigation encompasses a variety of technologies. They are used to identify characteristic elements of a 3D environment. To this end, 3D environment identification systems are used, based on measurements performed by optical sensors. This application is most typical for autonomous vehicle systems. The said sensors include cameras as well as the increasingly popular LIDAR system. All these devices make it possible not only to identify characteristic points in the environment, but also to determine their distance from the object being navigated. In the case of cameras, this requires the application of stereometry. There are numerous techniques and devices which can be used in this respect, in a more or less unreliable manner. LIDAR, for instance, proves to be among the high-accuracy methods applied in this sphere. The operating principle of LIDAR (Light Detection and Ranging) devices is based on a method of distance measurement in the visible light spectrum. For this purpose, objects in the environment are illuminated with laser light. The distance measurement in the system comprising the navigated object and the environment object takes place by determining the light beam reflection parameters. Differences in the laser beam return time and a wavelength change make it possible to create 3D models of the environment. In practice, however, the LIDAR technology encompasses an entire array of different solutions enabling terrain to be modelled by measuring the light beam reflected from objects in the environment. Nevertheless, numerous image processing problems are associated with this class of detection systems. Another kind of equipment commonly used in navigation systems is cameras. In this case, a solution known as computer vision is responsible for building traffic scene models, its task being the detection and tracking of specific characteristic points in the image (flat or stereographic representation of a 3D traffic scene). The use of a stereometric system of cameras makes it possible to obtain information about image depth, and by that means, about the distance from specific objects to the one being navigated. Therefore, the navigation methods which make use of devices operating within the light wavelength spectrum generally comprise registration of 3D point clouds in the vicinity of an object equipped with adequate sensors. For this purpose, you can use simple and cheap solutions such as Microsoft's Kinect or more advanced cameras, e.g. from Luxonis (https://www.luxonis.com/). An object with such sensors on board can detect external objects and, by that means, navigating (safely and without problems) in the environment (Kakoluaki et al. 2021; Hinsley et al., 2006; Lohani et al., 2017). The design of the special-purpose off-road vehicle for PwSN envisages the use of the GPS signal, while the system proposed in this article is considered as a backup, activated if the GPS signal is lost or disrupted. The system in question can also be operated with the GPS signal available, offering other additional features described further on in this article, which may promote its use independently of the GPS. Additionally, a vehicle intended for PwSN could be equipped with stereovision camera or LIDAR systems, yet all such solutions raise the vehicle price significantly, by a dozen or so (for stereovision) to event several hundred per cent (with the LIDAR on board) of its base value. Moreover, due to weather conditions, visual systems can be very unreliable in the mountains, which makes radio communication-based systems worth considering when retrofitting off-road vehicles for PwSN.

Mapping systems represent a solution of common application in navigation. They enable geometric modelling of the traffic scene environment, but they are not homogeneous. Mapping is performed slightly differently for stationary and moving objects, even though the related field of robotics can cover a broad range of aspects. The mapping systems typically designated with the acronym SLM (Simultaneous Localisation and Mapping) are used in environments where the GPS signal is disabled or not strong enough (e.g. in all interiors). The mapping which consists in building a 3D (traffic) scene model of an unknown environment constitutes primarily a computational problem. Using the SLM method, a 3D model of the environment is being constructed while the position of the navigated object, referred to as the *agent,* is simultaneously being updated. What proves to be critical with respect to the specifics of the environment (spatial structure and dynamics) and the speed of the navigated agent is the timing of the 3D environment model building (Jaulin, 2011; Cadena et al., 2016). One can also come across the notion of visual odometry (VO) when studying this body of problems. Navigation uses a visual signal only. Visual odometry is a process in which position and orientation are established by analysing related camera images (Comport et al., 2010, Aqel et al., 2016). Terrain relative navigation (TRN) is yet another technique which enables navigation, where data retrieved from vehicle sensors are matched with a map of the environment. The TRN type navigation makes it possible to position an object of interest against a map. This technique has been used to target specific landing points on the surface of celestial bodies (Mars 2020 mission) with an intent to improve the landing process accuracy and to avoid obstacles (Sanchez, 2021; Johnson et al., 2008; McCabe et al., 2020).

Bearing the foregoing in mind, about the navigation system proposed for special-purpose off-road vehicles for PwSN, the following engineering aspects should be identified and taken into account:

– atmospheric conditions, including rain, humidity, snow, solar radiation, ambient temperature,
– terrain conditions linked with the environment being modelled, including built-up area (city, suburb, foothills, mountains), terrain relief, elevation differences in mountain trails, path curvature, different types of ground,
– system configuration, including operating conditions (temperature, vibrations), on-board equipment (transmitters), on-trail reference equipment (receivers), antennas and components used in both these kinds of equipment, transmitter-receiver reference systems, number of devices, on-trail distribution density of devices,
– transmission parameters (frequency, directionality, other parameters: spread factor, bandwidth, etc.),
– system security (cybersecurity),
– operating conditions of the equipment (temperatures, power supply, receiver battery replacement),
– other interferences: mineral deposits, e.g. uranium, spoil used for road construction extracted from low-lying deposits.

Due to various odd results, each path object must be implemented in the system each time. Two geometrically similar paths can differ significantly in terms of transmission conditions.

GPS is unreliable in extreme conditions, for example, underwater and underground, in locations without GPS. These environments are supported by LoRa technology, which enables localization based on received signal strength (RSSI). LoRa allows for rapid localization in emergency situations without GPS availability. Rescue teams use it. The authors of this study claim that this is a promising solution for wireless localization systems in environments without GPS (Mackey, et al. 2019). On a similar topic, other authors analyze movements in dense forest environments, where GPS signal reception is difficult. They propose an intelligent forest navigation system by integrating LoRa communication, radar obstacle detection, and dynamic pathfinding. This involves measuring the time of arrival from LoRa nodes to long-range locations, improved by combining sensors with data from an IMU using an extended Kalman filter on the user's smartphone. The radar sensor is responsible for real-time perception of the surroundings, detecting obstacles and dynamically updating the map. Path optimization is handled by the D∗ Lite algorithm, which adapts to terrain changes and obstacle updates using a cost function that considers terrain difficulty and energy efficiency. The system offers a solution suitable for forest exploration, wildlife tracking, and search and rescue missions in GPS-disabled environments (Nevatia et al., 2025). Other researchers are developing a location monitoring system that utilizes LoRa, simultaneously analyzing detection range data, battery usage, and receiving signal strength. These are location monitoring systems that offer low power consumption but long range (Norlezah et al., 2021). As you can see, the scope of LoRa application in navigation systems is wide, although it often requires additional measurement and control devices.

3. Materials

Field studies of a navigation system intended for a special-purpose off-road vehicle for PwSN can involve testing of various components and devices, including LoRa systems (i.e. radio, radio module), antennas of different design, various types of microcontrollers, GPS receivers, and other auxiliary subassemblies for base measurement systems. The GPS systems are only used in the studies to keep track of the position of the communication system objects in the transmitter-receiver system. In this respect, one can essentially study some of the LoRa communication standards, namely 433/868 MHz (also referred to as LoRa LF and LoRa HI). In Europe, the LoRA applications are limited to licence-free radio frequency bands: EU433 (433.05–434.79 MHz) and EU868 (863–870/873 MHz). Sometimes specific local bands below both ranges can be used. In practice, these bands are similar to each other due to the relevant legal restrictions. There is also the *American band* of AU915/AS923-1 (915–928 MHz). They are often referred to as sub-GHz bands. The equipment chosen for the studies discussed in this paper operated in the EU433 band. These devices use a channel data structure (at least 16 channels). The first three channels correspond to the frequencies of 433.175, 433.375, and 433.575 MHz. The EN 300220 ETSI standard offers a maximum duty cycle of up to 10% in the EU433 MHz band. LoRaWAN requires a transmission duty cycle being 1% lower than the permissible limit. The second frequency band, i.e. EU863-870, corresponds to 868.1–868.5 MHz, respectively (ETSI, 2024). The EU863-870 band can be used in any region where the ISM radio spectrum is defined in the ETSI 307 standard. Terminal devices will operate in this band between 863 and 870 MHz. As aforementioned, the LoRa technology enables long-distance transmission with low power expenditure. It encompasses the physical layer, protocols, e.g. LoRaWAN (long-range wide area network), as well as higher layers. In the course of the analyses discussed, aimed at determining whether the LoRa solutions can be adapted to a navigation system, it was primarily decided that the tests should be conducted in the 433 (LF) band, since it comprised the cheapest group of devices which were actually responsible for limiting the transmission range. There are specific power limits imposed on both systems. It is also envisaged that a large number of devices should be installed on every single trail, and hence the importance of cost cutting. An average mountain hiking trail in Poland is between four and sixteen km long, rarely longer. Those of more than ten kilometres in length are referred to as *whole-day trails*, just long enough to reach a mountain hostel. Therefore, maintaining adequate organisation of the traffic of the special-purpose vehicles in question would require installation of hundreds of reference points on a single trail, at the least (which will be explained further on in the paper). Although these vehicles offer running ranges of up to 200 km, on account of the difficult terrain, their transfer time will not exceed that of foot traffic.

Fig. 1 shows four prototypes of a navigation system's transmitters and receivers designed for special-purpose off-road vehicles for PwSN. They are rather similar in terms of design. The difference between the individual prototypes boils down to the radio module used, while the transmitters also contain a GPS chip (which is not present in every receiver). These designs can also be expanded with a data logging system (containing storage devices and an RTC clock). The tests confirmed the good properties of EByte systems, which were praised on amateur forums. This module provides an effective and reliable range of up to several kilometres.

Fig. 2 shows three different setups of the radio used in the studies. Radios differ in terms of frequency and often in gain. The 433 transmitter (Fig. 2a and c) consists of four components: a microcontroller (ATmega UR3 in this case), the NEO-6M GPS receiver with a ceramic antenna, the Ra-02/E220 LoRa chip, and a 5dBi omnidirectional antenna (AI-THINKER,Ra-02, 2024; DFRobot, FireBeatle, 2024). The ESP32 WROOM microcontroller and the LoRa FireBeetle module were used in the 868 radio transmitter (Fig. 2b) (AI-Thinker, Ra-02, 2024; DFRobot, FireBeatle, 2024). The LoRa modules used in the studies have been shown in Fig. 2 along with the wiring required for connectivity with the microcontroller. The cost of the respective modules ranged between PLN 35 and PLN 89, as of July 2024 (in an ascending price sequence: RA-02, Ebyte, FB). The cost of the entire transmitter/receiver setup, without enclosure, ranged from approx. PLN 100 to 160, depending on the radio configuration and accessories used. The abridged characteristics of individual radios have been provided below, as specified by their respective manufacturers. RA-02 module specs: SX1278 chip, receiver sensitivity: 141 dBm, SPI interface, rate up to 300 Kbps, frequency range: 410–525 MHz, U.FL/IPEX antenna connector, max. power: 18±1 dBm, power consumption at 433 MHz: TX – 93 mA, RX – 12.15 mA, standby mode: 1.6 mA, power supply voltage: 2.5–3.7 V. FireBeetle module specs: frequency: 868 MHz, modulation: LoRaTM, FSK, GFSK, OOK, output power: ≤20 dBm, receiver sensitivity: -139 dBm, emission current: ≤120 mA, receiver current: ≤15 mA, sleep current: ≤0.2 uA, transmission power range: -1dBm to 20dBm, transmission mode: FIFO/DMA, operating frequency range: 800 MHz to 900 MHz, distance: 5 km, transmission rate: @FSK – 1.2300 Kbps, @LoRaTM – 0.01837.5 Kbps, SPI interface, GPIO: 5, voltage: 3.3 V, operating temperature: -20°C to 70°C. Ebyte module specs: frequency: 410–493 MHz, sensitivity: -147 dBm, rate: 2.4–62.5 kbps, distance: 10,000 m, UART communication interface, antenna outputs: SMA-K, power supply voltage: 3.3–5.5 V, power consumption in standby (deep sleep): 5 uA, power consumption in operation @30 dBm: 620 mA, max. operating humidity: 90%, operating temperature: -40 to +85. The above data have been provided directly from the module manufacturers' brochures (AI_Thinker Ra-02, 2024;DFRobot FireBeatle, 2024). In the context of setup, you should always remember about local conditions of use, otherwise it may end up with a fine.

Fig. 3 is a schematic representation of the transmitter and receiver used in the navigation system subject to the studies. The LoRa radio circuit is connected to the microcontroller; similarly, the GPS module is connected to the transmitter unit, its purpose being the identification of the vehicle position. What can be used to build the transmitter and receiver is a programming platform intended for microcontroller-based systems, mounted on single printed circuit boards. Both the transmitter and the receiver can be equipped with add-on units containing a data storage and management module. Such a system features, as a minimum, an external data storage unit (usually an SD card) and a real-time clock (RTC). An antenna connected (in various ways) to the radio module completes the set. We use communication systems with almost all popular microcontrollers available on the market.

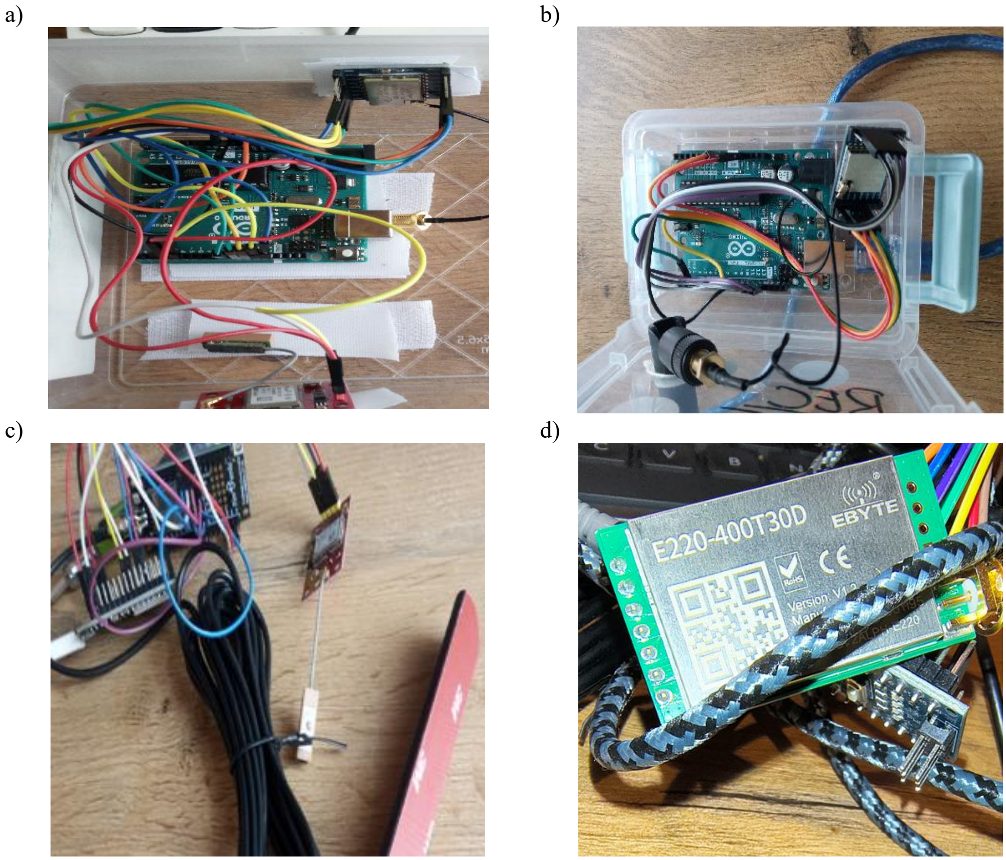

Fig. 1. Model prototype of: a) 433 transmitter, b) 433 receiver, c) 868 transmitter d) another 433, better in range transmitter. Source: own photo

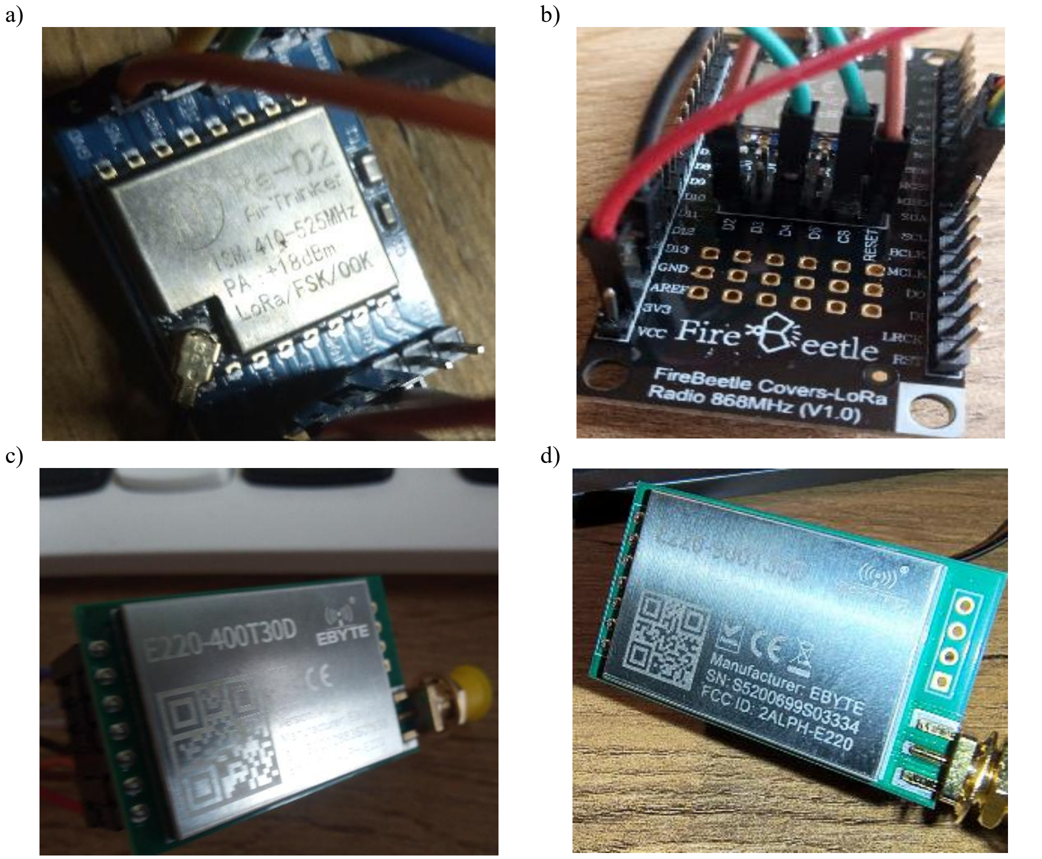

Fig. 2. LoRa modules used in the studies: a) Ra-02, b) FireBeetle, c) Ebyte of the 220/400 series, d) Ebyte of the 220/900 series. Source: own photo

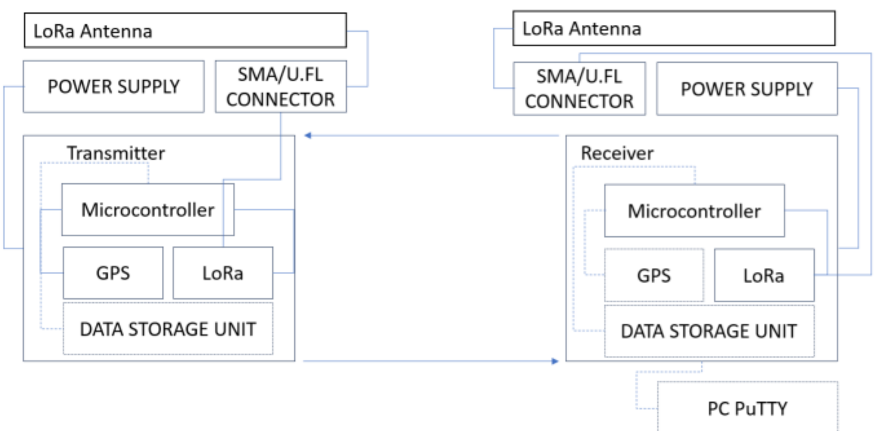

Fig. 3. Transmitter and receiver setup diagram. Source: own elaboration

Fig. 4 shows the terminal windows of both devices: the transmitter terminal window in Fig. 4a and the receiver terminal window in Fig. 4b. Being able to monitor the transmitter and receiver ports, one can control the transmitter and receiver status. However, one should also bear in mind that the GPS transmitter does not start transmitting until its position has been fixed, which causes a delay in sending data to the receiver (from several to even more than ten minutes in this class of equipment, depending on conditions).

Another kind of studies of the off-road vehicle's navigation system intended for PwSN comprises analyses performed against the trail configuration. People with special needs typically travel by means of special-purpose vehicles starting from a specific point of origin, namely urban areas (railway stations, car parks, bus stops, vehicle rental shops), and such trails continue through foothill areas to enter mountains, including high mountains, turning from local roads into typical hiking and mountain trails. Therefore, signal strength propagation analyses for navigation system equipment should be conducted in three cross-sections: urban, suburban, and mountainous, using different transmitting and receiving devices, conforming with standards 433 and 868. Such a cross-section of analysis will then be complemented with a signal measurement using various transmission parameters (spreading factor, bandwidth, etc.). Table 1 shows typical transmission parameters as per the LoRa standard.

Fig. 4. Sample transmission parameters; terminal window (data on print screen in polish) of: a) transmitter, b) receiver. Source: own elaboration

Table 1. LoRa transmission parameters

Spreading factor [-]	Bit rate [bps]	Range [km]	Time on Air [ms] 11 byte payload	Announcement/h/m
12	250	>8	1,318	27/1
10	980	8	371	100/2
9	1,760	6	185	195/3
8	3,125	4.	103	350/6
7 (default)	5,470	2	61	590/10

The problems in question were studied for different spreading factor values (SF = 7–12). It should be noted that although increasing the SF value makes it possible to achieve greater ranges, it also entails an increase in transmission time. Therefore, one should seek an optimised combination of transmission parameters that will enable the required amount of information to be sent over a given distance. The test results have been presented in Fig. 5.
Fig. 5 a and b show results of the LoRa signal measurements for the spreading factor settings of SF=7 and SF=12 in a built-up area (city centre). SF=7 is the default setting of the software used. It is envisaged that the LoRa signal is to be measured for the same combinations of settings in other terrains: suburban and mountainous, as well as for different local conditions. The aim of these studies is to select the optimal transmission parameters and to establish receiver siting rules.
Fig. 6 shows the signal characteristics measured at the navigation system receiver. All these characteristics refer to the setting of SF=12. The following pieces of information have been provided, sequentially: RSSI (signal strength), SNR (signal-to-noise ratio), and frequency deviation from the channel average.

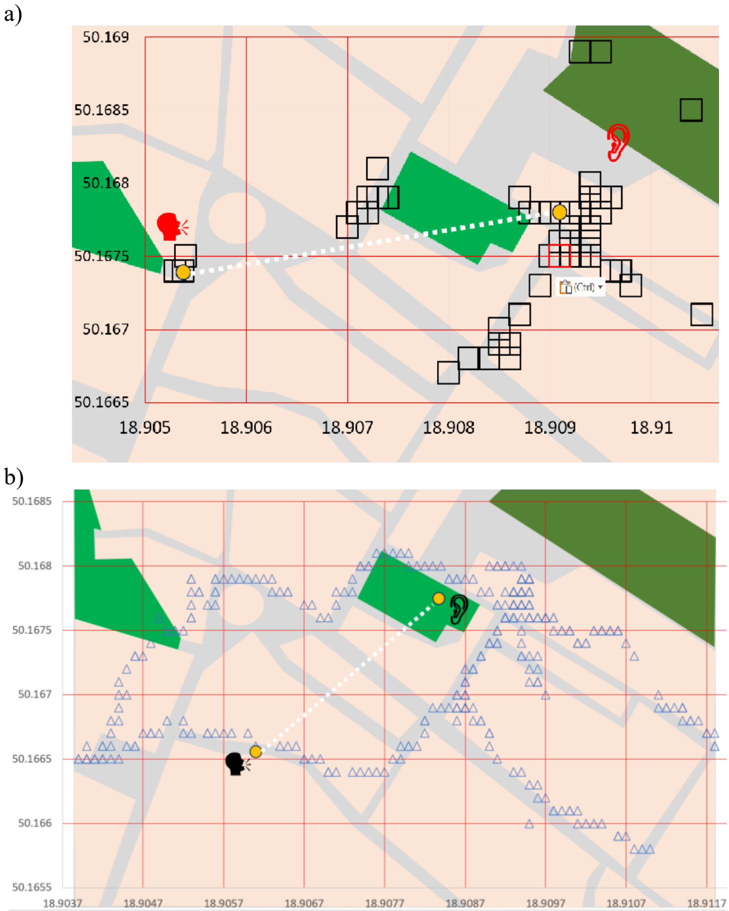

Fig. 5. LoRa range analysis: a) 433 SF=7 – urban area, city centre, high rise buildings, b) 433 SF=12 – urban area, city centre, high rise buildings. Source: own elaboration

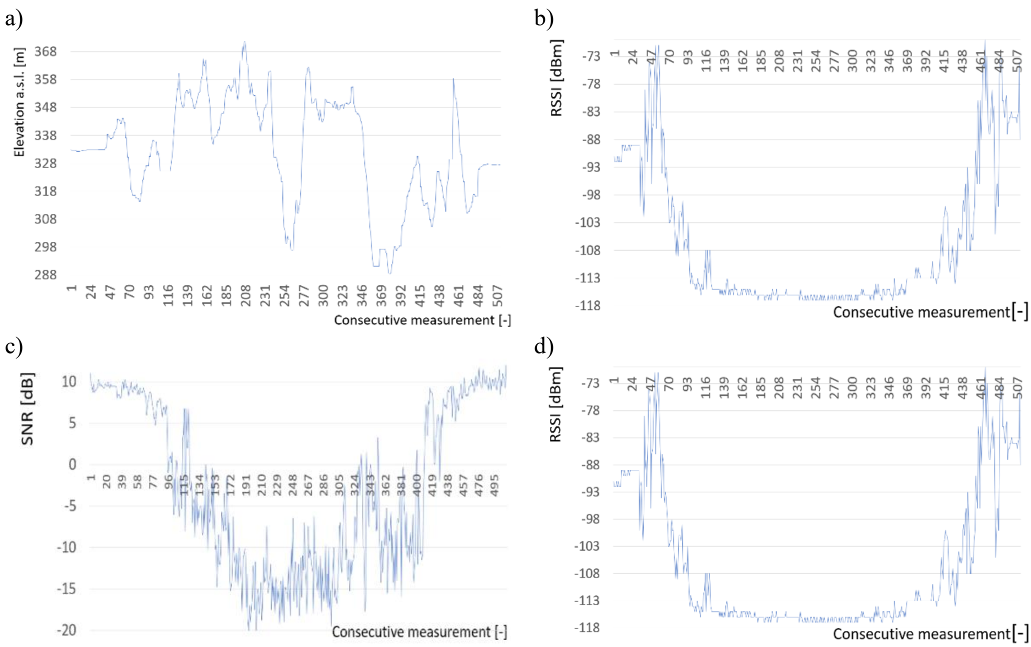

Fig. 6. Signal parameters for SF=12: a) elevation b) RSSI c) SNR d) PF_error. Source: own elaboration

Table 2 summarises average vehicle headway values for the different transmission parameter configurations. While conducting the tests and analyses in question for the different transmission parameters of the navigation system, it was decided that further tests should be performed for two combinations: SF=8 and SF=9. Both these transmission settings provide sufficient communication quality along with high information capacity. Fig. 7 illustrates testing of the navigation system's signal in a built-up area for the said transmission parameter settings.

What can be deduced from an analysis of the data provided in Fig. 7a and 7b (by visual observation) is that the area coverage for both transmission parameters is similar. More information can be derived from the signal evaluation values: RSSI, SNR and P_f_err. Table 3 provides a summary of the numerical characteristics of the dataset collated for these transmission settings.

Table 3 contains results obtained for the RSSI, SNR and p_f_ERR characteristics measured for the signal analysed in different variants, for SF=8 and SF=9. The RSSI parameter (Received Signal Strength Indication) defines the power index of the radio signal received. It means that this parameter indicates how well a given receiver can receive data from a transmitter connected to a LoRa system (as in this case).

Table 2. Headway calculation for messaging / SF=9, SF=10, 6 messages. Source: own elaboration

Speed [m/s]	Speed [km/h]	Speed [m/min]	Average headway for SF=9 [m]	Average headway for SF=8 [m]	Number of vehicles *[-].
2	7.14	120	20	10	2
4	14.29	240	40	20	3
6	21.43	360	60	30	4
8	28.57	480	80	40	4
10	35.71	600	100	50	4
12	42.86	720	120	60	4
14	50.00	840	140	70	4

* – adopted buffer of 2 m +1*v [m]

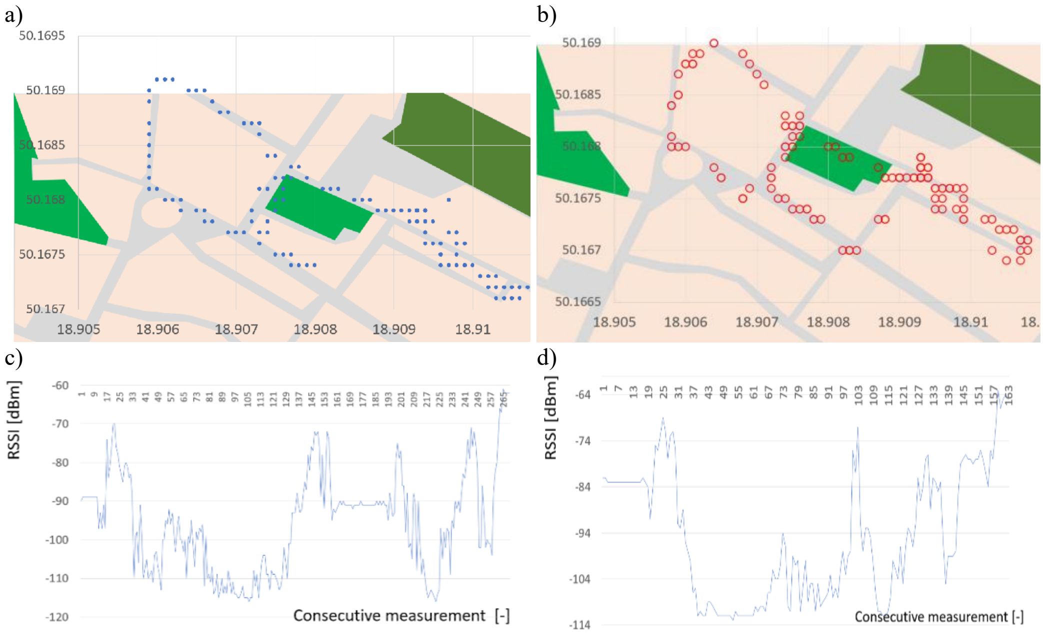

Fig. 7. Transmission comparison for different parameters: a) access point at SF=8, b) access point at SF=9 c) RSSI at SF_8 d) RSSI at SF_9. Source: own elaboration.

Table 3. Comparison of statistical parameters of signal evaluation for SF=8 and SF=9. Source: own elaboration

	RSSI [dBm]		SNR [dB]		P_f_ERR [Hz]	
SF	8	9	8	9	8	9
AVG	-94.8	-94.6	8.66	6.58	422.7	1,603.3
MED.	-92.0	-98.0	11.50	10.00	465.0	1,608.0
DOM	-89.0	-112.0	12.00	9.75	473.0	1,633.0
STD	12.5	14.2	5.87	7.63	200.1	27.7

The signal weakens as the transmitter and receiver are moved away from each other, which is illustrated by the decreasing RSSI value. It is measured in dBm. It is evident that the average RSSI is similar for both transmission parameters. The waveform of the RSSI characteristics is also similar in both cases (Fig. 7c and 7d). SF=8 is the setting which appears to offer better transmission parameters (dominant and modal value). What Table 3 also shows is the signal-to-noise ratio (SNR). It is used to measure the strength of the desired signal relative to the background noise. Background noise is regarded as an undesirable signal (there is a lot of such noise in a typical space, especial in urban areas). SNR is defined as the ratio of the power of a desired signal to the power of background noise, and it is expressed in decibels (dB). The higher the signal-to-noise ratio, the better. Table 3 implies that the SF=8 setting appears to be superior in this respect. The next parameter, i.e. P_f_ERR (packet frequency error), returns the frequency error of a received packet in Hz. The frequency error is determined by the frequency offset between the mid-channel frequency of the receiver and the frequency of an incoming LoRa signal. The frequency error is the estimated frequency offset of the signal received from the mid-channel frequency, expressed in Hz. The larger the error value, the worse. For standard receiver and transmitter settings of BW=125k, this error should not exceed a few hundred hertz. Therefore, it is evident that the values obtained for SF=9 are unsatisfactory. Based on the analyses performed, the SF=8 setting was adopted for further measurements performed in mountainous terrain, focused on studying the navigation system infrastructure and its configuration. With more favourable bandwidth parameters, this setting is characterised by twice the information transmission rate. The graphs below illustrate the results of the said measurements in terms of the impact on transmission quality: slope, trail curvature, weather conditions.

Fig. 8a depicts the signals received in the transmission quality test conducted on a hill of varying slope (expressed in %). Each time, configurations of an intersection of two mountain trails were tested (Fig. 8a). The RSSI test results have been provided in Fig. 8b–h. It is noteworthy that the RSSI values presented in Fig. 8b–h were established for a specific slope. Therefore, the value of 100% represents a slope with an inclination angle of 45 degrees. Each time, the receiver was located higher up and in front of the moving vehicle. An analysis of Fig. 8b–h implies that, in general, the signal thus received was of good quality, which appeared to be the worst for the receivers located at or near the same level as the approaching or receding off-road vehicle for PwSN (up to 5%). As the slope increased, the signal would improve (the receiver being always higher on the slope than the vehicle). With the vehicle being even slightly higher than the receiver, the signal could improve by 10 to 20 dBm. Above the slope of 30%, these improvements came only to 10%. Further up, as the elevation difference between the receiver and the transmitter increased, the signal deteriorated, but remained within a decent quality range. The data provided in Fig. 8 were discretised by truncating the accuracy of the position measurement to reduce the data in the message. The average RSSI values obtained for the respective slopes analysed have been summarised in the table below (Table 4).

As a reminder, Fig. 8 illustrates the measurement results obtained in the transmitter-receiver system for different slope ranges (up to 45%). The foregoing stems from the studies discussed further on in the paper, where several popular Polish trails were parameterised in this respect. Slopes exceeding 40% can be encountered on very small sections of typical mountain trails. The case of high mountains is not interesting from the point of view of the authors' research anyway, since the special-purpose vehicle in question will not be fit for operation in many of such areas. It should be noted that the phenomenon of signal improving with the growing elevation difference between the transmitter and the receiver increases is accompanied by a loss of measurement data. The data loss is proportional to this elevation difference. However, this can be compensated for by selecting the right type of antennas, or by using different antenna configurations. What would also need to be examined is the problem of minor elevation differences encountered during the studies.

In the months to come, further analyses will be conducted to investigate the effect of trail curvature on the navigation system being designed and its structure. They will be based on studies previously carried out with regard to this parameter for several reference trails. Three different types of curvature will be taken into account in the test area: perpendicular, parallel, and diagonal against the direction of the vehicle movement. Another important part of the research is determining the number of vehicles that can use the trail in terms of the navigation system in operation. The first constraint thereto is the infrastructural limitation connected with the trail capacity. This is a complex issue, as discussed at the end of this section, related to junctions on mountain trails, passing points, etc. Another constraint is directly linked with the navigation system considerations. As previous research implies, the very high number of stations operating in the LoRa system causes latency and other technical issues in need of clarification. One of such research fields is a short 2 km section with elevation gains of up to 10 meters and considerable winding.

The route shown in Figure 9b is very interesting because it is characterized by sudden signal drops. Declines caused by the coincidence of changes in height and sinuosity, but with relatively small values of these changes.

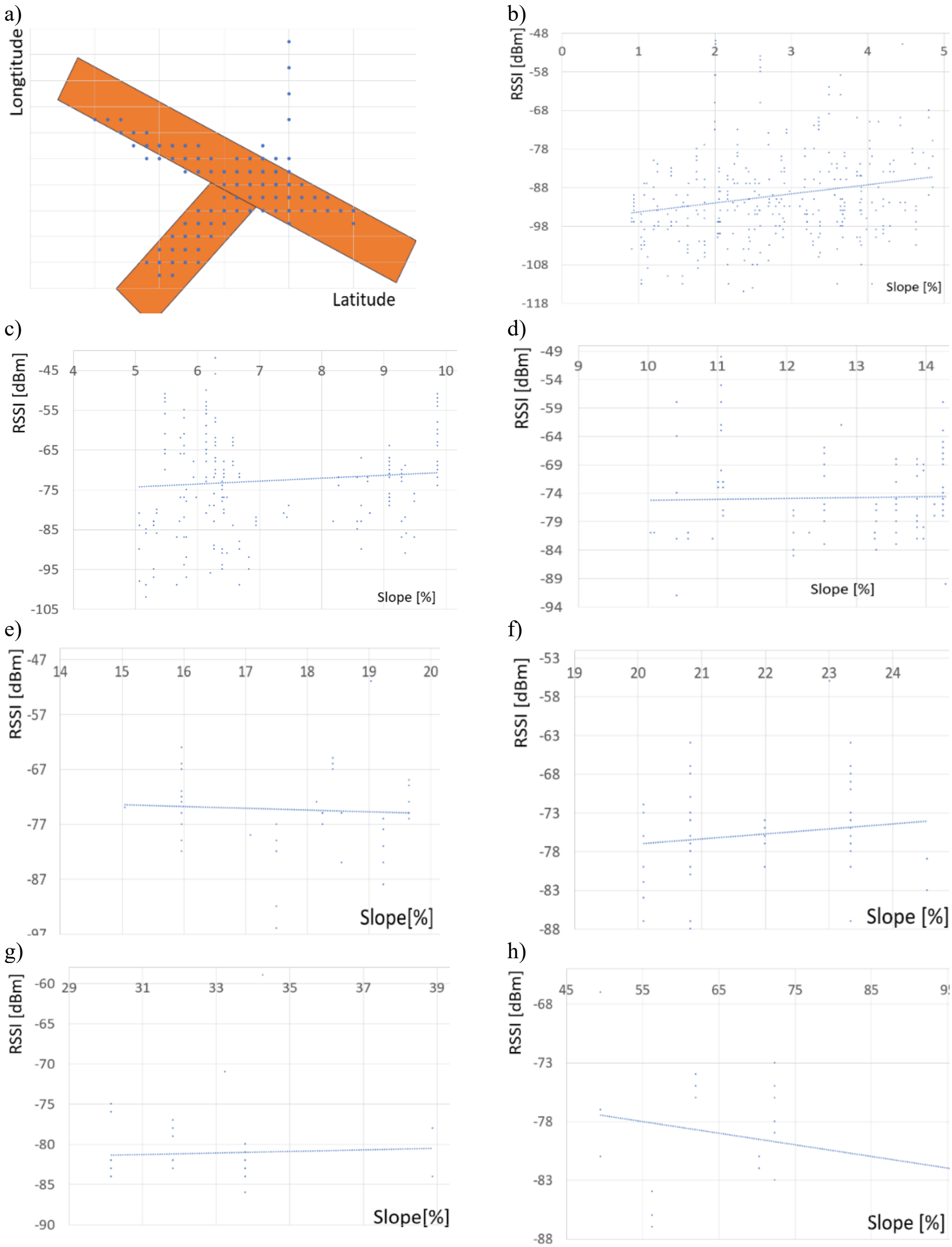

Fig. 8. Analysis of LoRa coverage in mountainous terrain (for SF=8): a) layout of read-outs, slope: b) up to 5%, c) 5–10%, d) 10–15%, e) 15–20%, f) 20–25%, g) 30–40%, h) >40%. Source: own elaboration.

Table 4. Average RSSI values for individual slopes. Source: own elaboration

Slope [%]	**0–5**	**5–10**	**10–15**	**15–20**	**20–25**	**30–40**	**>40**
AVG RSSI [dBm]	-90.2	-72.8	-74.8	-74.3	-75.8	-81.1	-80.0

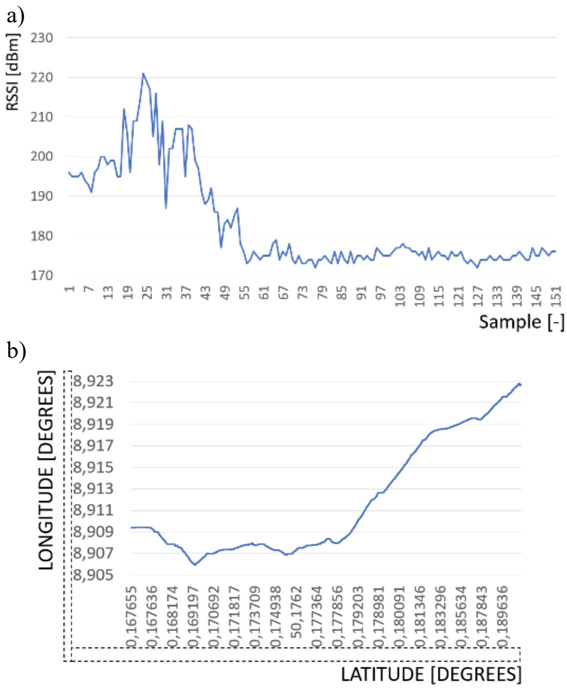

Fig. 9. Analysis of LoRa coverage in section selected for research a) RSSI b) section layout

4. Navigation system and mountain trail parameters

The following paragraphs provide analyses of mountain trail parameters which may condition the structure and features of the navigation system being designed. They include trail curvature, on-trail slope profile, profile of trail sections, etc. These analyses have been illustrated for four popular mountain trails in Poland.

Fig. 10 shows the elevation and slope profiles of four different mountain trails located in the territory of Poland. They are as follows: Węgierska Górka–Rysianka (blue colour, trail no. 1), Karpacz–Śnieżka (red colour, trail no. 2), Sękowiec–Dwernik (green colour, trail no. 3), and Ustroń Polana–Równica (black colour, trail no. 4). The colours used in this article have nothing to do with the colour coding of trails for tourism purposes. They are all popular Polish mountain trails located in the following mountain ranges, respectively: Beskid Żywiecki, Karkonosze, Bieszczady, Beskid Śląski. The elevation and slope profiles of these trails were approximated using a service which makes it possible to determine the elevation of a chosen point in the terrain (Calc Maps, 2024). The GPS coordinates of some characteristic points of each trail were also used in these calculations (an attempt was made to map successive trail sections as accurately as possible). The route of each trail was determined using one of the available Polish tourism services (Mapa Turystyczna, 2024). This is a rather rough procedure, but the authors still believe it to be superior to using elevation data obtained from cheap (popular) GPS receivers whose greatest errors typically pertain to elevation (according to the authors' tests). In the future, these data will be established with reference to direct measurements using IMUs. However, such scanning of all mountain trails is beyond the scope of this study at this point in time.

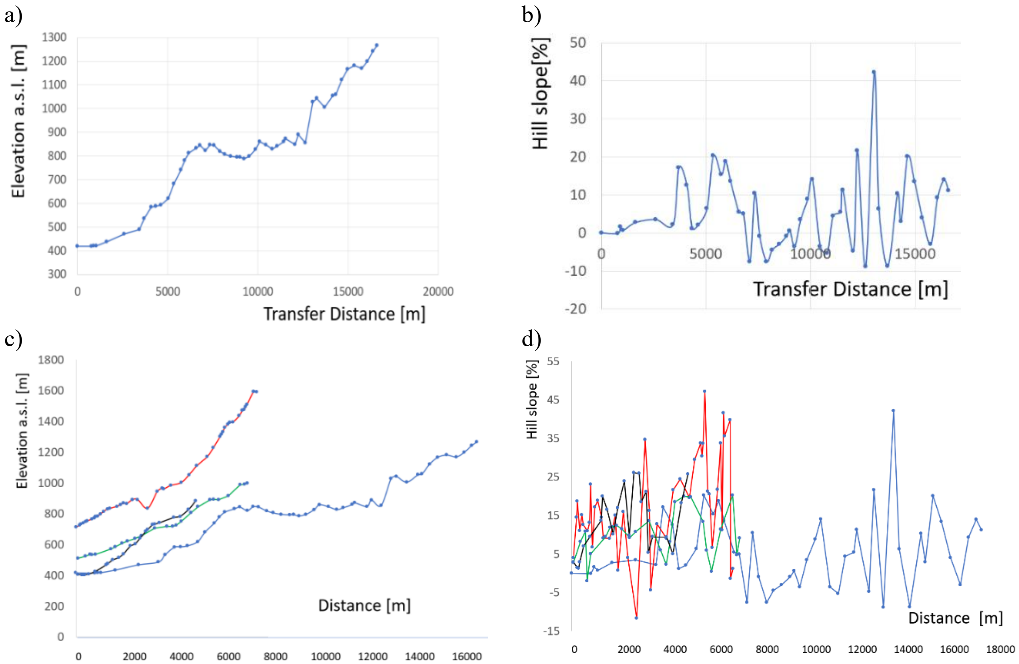

Fig. 10. Elevation and slope profiles of selected mountain trails in Poland: a) Węgierska Górka–Rysianka – elevation profile, b) Węgierska Górka–Rysianka, slope, c) four trails chosen for the study, collectively – elevation profiles, d) four trails, collectively – slopes. Source: own elaboration

Table 5. Statistical data of selected mountain trails. Source: own elaboration

Trail name	Węgierska Górka–Rysianka		Karpacz–Śnieżka		Sękowiec–Dwernik		Ustroń Polana–Równica	
Elevation [m] / slope [%]	h	N	h	n	h	n	h	n
AVG	817.8	5.61	1,064.9	11.59	719.2	6.68	578.7	9.58
Median	828.5	3.76	961.0	9.79	710.0	6.44	577.0	6.74
Dominant	845.0	-	835.0	0.00	520.0	-	379.0	0.00
STD	229.2	9.65	296.9	11.19	170.3	5.68	165.2	7.79

Table 5 shows the numerical characteristics of the dataset parameterising the mountain trails chosen for the studies. The mean, median, dominant, and standard deviation values have been provided, in this exact order, for the trail elevation and slope. What can be derived from the data thus obtained is some specific conclusions for the implementation of a navigation system designed for a special-purpose off-road vehicle intended for PwSN. These mountain trails were selected intentionally, all of them characterised by varying difficulty and time required to traverse, but at the same time, they were to a large extent suitable for MTB (mountain bike) exploration (their adaptation for off-road vehicles for PwSN would sometimes require additional measures). The following insights relate to the data provided in Figures 9a–d. There are long ascending and descending sections on the trails analysed, such as those on trail no. 1. With some minor elevation changes being disregarded, an entire trail can be said to ascend steadily upwards (trails no. 3 and 4). Where there are long ascending and descending sections, like on trail no. 1, the density of the potential traffic stream of off-road vehicles for PwSN is changing.

In the study, we distinguished 11 research hypotheses: density/speed correlation, hill drops/speed correlation, congestion on specific elevations, small traffic- small access point, rush hour on trails, profile-stream correlations, pedestrian-vehicle strong interaction,

On long hills going up, traffic speed decreases while traffic stream density increases **(hypothesis 1).** Conversely, on long hill drops with good infrastructure, speed can increase and traffic stream density typically declines **(hypothesis 2).** What stems directly from these hypotheses is that a change of the number of reference points on these trail sections is necessary (without even pre-assuming their spatial arrangement). For long sections, where the receivers assumed for the off-road vehicles for PwSN will be installed in hundreds of pieces, this conditions certain specific problems for the LoRa system, such as e.g. increased transmission latency times. A larger number of transmitters requires an increase in the number of receivers. In shorter sections of variable elevation (as on trail no. 2), there can be abrupt changes in the conditions relevant to the traffic stream, which may cause congestion at characteristic points on the trail, i.e. at local extremes of elevation profiles **(hypothesis 3).** This can also lead to on-trail incidents and accidents. Long upward elevation sections of uniform (trails no. 3 and 4) and exponential characteristics (trail no. 2) may cause speed changes as the trail is traversed (and increasing fatigue without any means of assistance employed), potentially leading to changes in the density of traffic streams with different stochastic characteristics **(hypothesis 4).** This being the case, it is likely that the spatial distribution of the LoRa receivers may be trail-specific. As a side note, such a situation calls for the construction of resting places on mountain trails. What can be observed on initial flat sections of trails (practically on all the trails discussed in the paper) is very fast traffic of the off-road vehicles for PwSN **(hypothesis 5).** In all likelihood, this makes it possible to use a small number of receivers. At peaks (and other destination points), on account of longer standstill times, congestion of the traffic stream and long standstills may be observed **(hypothesis 6).** This calls for a change in the organisation of the navigation system (for low and no traffic speed), which should be different there than at sites characterised by relatively high traffic speeds. Certain distinctive on-trail locations, such as peaks, will be associated with a change in the vehicle traffic sequence, which needs to be considered when preparing assumptions for the system **(hypothesis 7).** One can come across hillsides of sequential slope changes of high values (descent-ascent, ascent-descent – trails no. 1 and 2). Such a sequence of several consecutive abrupt profile changes can lead to changes in the density and intensity of traffic streams **(hypothesis 8).** Different traffic directions, in addition to the specific requirements for the navigation system infrastructure and software, result in vehicles being forced to pass each other on the trail. Unlike in foot traffic, where the passing of people does not pose major difficulties (on many trail sections), this is not possible for vehicles on most typical trail sections. It can also lead to changes in the traffic stream parameters of off-road vehicles for PwSN at these locations **(hypothesis 9)**. There is yet another problem connected with the interaction between special-purpose vehicles for PwSN and those travelling on foot, which will change vehicle traffic characteristics (**hypothesis 10**).

Under typical Polish conditions, average elevation profiles do not entail restrictions on the use of special electronic systems, while the system itself is supposed to be cheap, after all (Table 5). The average elevation of tourist trails rarely exceeds 1,000 m a.s.l. The standard deviation of the elevation profile is a good measure of the trail difficulty as well as of the navigation system configuration requirements assumed for special-purpose off-road vehicles for PwSN. In order to make practical use of the statistics provided in Table 5 for purposes of configuration of on-trail navigation systems, parameterisation of a larger number of mountain trails in Poland is required. A dedicated method will be developed to this end, based on artificial intelligence techniques and the use of drones. This will make it possible to automate and speed up studies of similar nature. The configuration of the navigation system is also affected by a particular parameter of mountain trail curvature. Curvature of each path is the ratio of the sum of the absolute values of the angles at which the path (road) turns, expressed in degrees, to its length, expressed in kilometres. The above definition has been adopted after the Regulation of the Minister of Transport and Maritime Economy of 2 March 1999 on the technical conditions to be met by public roads and their location (Journal of Laws no. 43, item 430, 1999).

Fig. 11 shows the routes of the tourist trails analysed in the studies. They are evidently characterised not only by different elevation profiles, but also by different curvatures. The choice of the points in which the receivers are to be installed is conditioned by the mountain trail curvature, since trail sections may overlap with considerable curvature (omnidirectional transmission case). One solution to this problem may be using directional transmitters. The system features diverse means of communication protection. One of these safeguards is the synchronisation of transmitters and receivers. Another viable option is encoding. The possibility that signals from different receivers overlap (technically, this problem can be solved in different ways) is best seen in Fig. 12.

Fig. 12 shows the difference in curvature between the climbs to the Śnieżka massif and to that of Równica. It is evident that both these trails, at different sections, are characterised by radically different curvature ratios. When calculating curvature, one should bear in mind that the actual operating speed [km/h] decreases as curvature increases (>250, 70 km/h). An example of such a calculation is provided in Table 6.

Fig. 11. Routes of mountain trails: a) Węgierska Górka–Rysianka, b) Karpacz–Śnieżka, c) Sękowiec–Dwernik, d) Ustroń Polana–Równica. Source: own elaboration

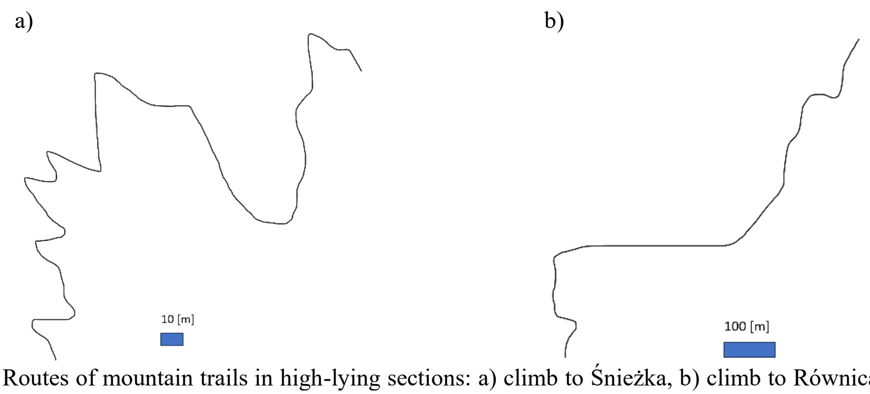

Fig. 12. Routes of mountain trails in high-lying sections: a) climb to Śnieżka, b) climb to Równica. Source: own elaboration

Modelling of tests of the LoRa system in difficult terrain is important, as evidenced in publications on this subject matter, including those concerning not only mountainous terrain, but also subtropical land conditions (Murdyantoro et al., 2019; Sarko et al., 2022).

Table 6. Example of mountain trail curvature calculation. Source: own elaboration

Trail/curvature	Ustroń Polana – Równica
[deg/km]	500

5. Operating principle of the system

The navigation system will essentially consist of sections into which each mountain (hiking) trail is to be divided as well as junction points where sections of different trails meet. On account of the conditions specific to each trail (elevation profile, curvature, surface type, forest cover, etc.), the sections will not be of identical length. Therefore, one must first define the operating conditions, organisational layouts, and algorithms for the navigation system.

Fig. 13 provides a schematic representation of three intersecting mountain trails (k, l, p). Each trail (marked as a) consists of consecutive sections (e.g. k^{th} trail with sections $k^1 ... k^n$). Each section has its length (l) and width (w) defined, and it is additionally designated in terms of curvature (c) and slope (s). Intersection points, where it is possible to apply the right-of-way rule on account of the traffic volume, are marked with the letter j (junction). Since trails can intersect multiple times, junction indices additionally feature a designation of the section of a given trail which is followed by the trail intersection. Therefore, the number of devices and their configuration can be expressed as the following function:

$$q_a^i = f(c_{ai}, s_{ai}, l_{ai}, w_{ai}, j_{ai} \ldots) \quad (1)$$

where:
c_{ai} – curvature of the i^{th} section of trail a [deg/km],
s_{ai} – slope of the i^{th} section of trail a [%],
l_{ai} – length of the i^{th} section of trail a [m],
w_{ai} – width of the i^{th} section of trail a [m],
j_{ai} – parameters of junction, if present, for the i^{th} section of trail a.

This is how the number of end devices to be installed on a given trail section is determined. It is difficult to establish at this point whether one can develop a formula which will enable full automation of the process in which the mountain trail navigation system infrastructure is designed. The standards and regulations in force which currently apply to the LoRa frequency band are diversified. The foregoing mainly pertains to the 1% hourly limitation on the amount of time each device can transmit information, which corresponds to 36 seconds per each hour. The antenna power limitation is yet another issue, as it can be no more than 10 and 14 dBm for 433/868. For SF=8, the maximum data transmission rate is 3,125 bps (bits per second). A distance over which the device will be able to send a message of 11 bytes is approx. 4 km, and it will take approx. 103 ms to send this message.

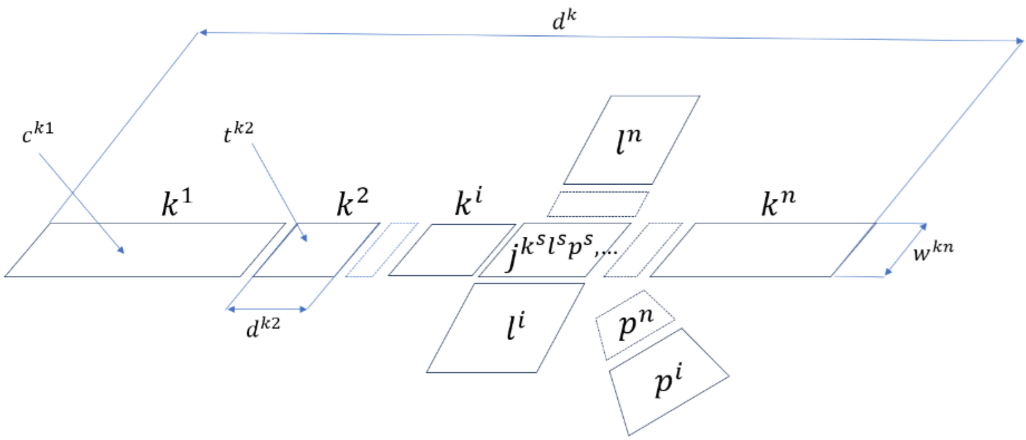

Fig. 13. Configuration of mountain trail sections. Source: own elaboration

The navigation system concept still requires the information frame to be defined. Table 1 provides the transmission time for a message based on what is commonly referred to as an 11-byte payload. With such transmission settings and for SF=8, the transmission time (103 ms) means approx. 350 messages per hour, and six messages per minute. This implies that the interval between messages would be ca. 10 sec. In order to save time, messages of six bytes each will be envisaged. This will make it possible to increase the transmission frequency by a factor of two, making such a navigation system capable of transmitting a signal every five seconds. In each message, these bytes must contain at least the following information: travelling direction, vehicle number, receiver number, travel origin and destination, and mountain area (range).

It is proposed that the vehicle number should be encoded using 12 bits, yielding 4,095 unique vehicle numbers for each of the areas included in the plans. Mountain chains are assumed to be delimited and broken down into ranges, where such traffic will be organised and managed independently. The delimitation will be dynamic in nature, meaning that the areas will be capable of *breathing*, as is the case of new generation mobile networks. For the Karkonosze mountains, with an area of 650 km^2, this translates into a density of 0.15 vehicles per km^2.

The receiver (reference) number is planned to be stored using 14 bits, giving a total of 16,383 receivers in the area-specific subsystem. The receiver spacing of 100 metres means that 1,638 km of mountain trails can be monitored (these distances will obviously vary depending on the trail specificity). With an average trail length of approx. 15 km, ca. 109 typical (regular) trails need to be covered. One should rather disregard longer trails on account of day-long mountain hiking limitations. Except in short sections on flat terrain, vehicles will also not reach speeds that are significantly higher than that of a hiker. 16,400 receivers translate into a cost of up to ca. PLN 1.6 million, being the maximum for the most densely covered mountain area. On average, a few hundred thousand zlotys needed to equip a mountain trail with the required navigation infrastructure (which can also help hikers) is not much. In terms of the terminology in use, note that the *receiver* is given the meaning specific to this study on account of the fact that it receives signals from vehicles which are transmitters and are equipped with the GPS devices, but this is essentially a two-way communication. And this will also be the case of the system in question once it has been commercialised, enabling the person using the special-purpose vehicle for PwSN to send an SOS signal, for instance. This will also make it possible to query the navigation system about traffic conditions (intensity, collisions, congestion, etc.).

The travel origin and destination orientation is not necessarily tantamount to the direction of traffic (the driver can turn around at any time by changing the traffic direction as well as the onward path, especially in a dense road network). The vehicle is assumed to traverse an area where 16,383 reference points can be installed, but also some of them will function as points of input and output to and from the system. These points form the OD matrix for the system being designed. There are 511 such points, i.e. five per each trail, on average. Therefore, for each trail, a start and an end can be defined, as well as three intermediate points where, for instance, one can stay overnight. Consequently, the current traffic direction can be determined by combining the origin point, the destination point, and the reference point currently being passed. It is further envisaged that the origin and destination data of each journey will be entered for security reasons. These parameters are to be entered by the user when entering the navigation system. Finally, each message will contain the reference number of a given mountain area, and there are 15 of them which may border each other. Therefore, the entire system should be developed towards such mountain area delimitation that it comprises no more than 15 bordering mountain ranges. With the SF parameter equalling 8, such a message can be updated approx. every five seconds.

The following is a concise description of the system's operating principle (Fig. 15). Setting off on a given route, in each mountain range (subsystem in the system, 1..15), the user of a special-purpose vehicle intended for PwSN logs into the system. Up to 4,095 vehicles can be logged into a single system (i.e. one mountain range). What one defines in this procedure using a smartphone application is the travel origin and destination, or possibly also intermediate points. When passed, each reference point (each of 16,383 in the subsystem) updates the current position of the PwSN's vehicle. This makes it possible to keep track of its position in the central system and, if necessary, undertake specific countermeasures, such as notifying the Mountain Volunteer Search and Rescue service (GOPR) in the event of an emergency. The system stores information on the current position of 4,000 vehicles within a given area, i.e. nearly 62,000 throughout the country. It enables efficient organisation and management of this traffic. For example, information on the sections occupied by vehicles makes it possible to identify traffic volumes, places of congestion, and collisions. Consequently, traffic can be optimised in the future based on the experience gained. Traffic light systems can even be deployed on particularly difficult trail sections.

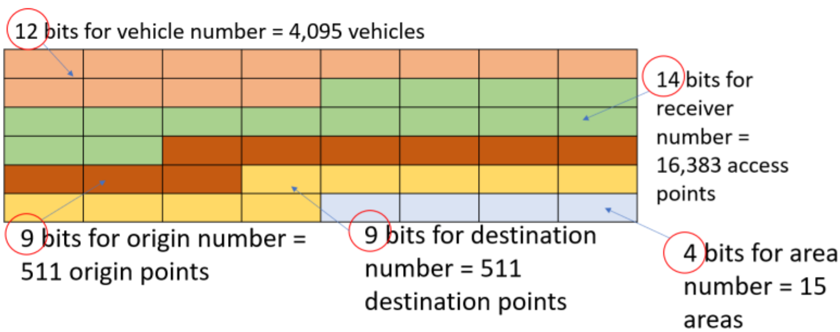

Fig. 14. Structure of the navigation system's message. Source: own elaboration

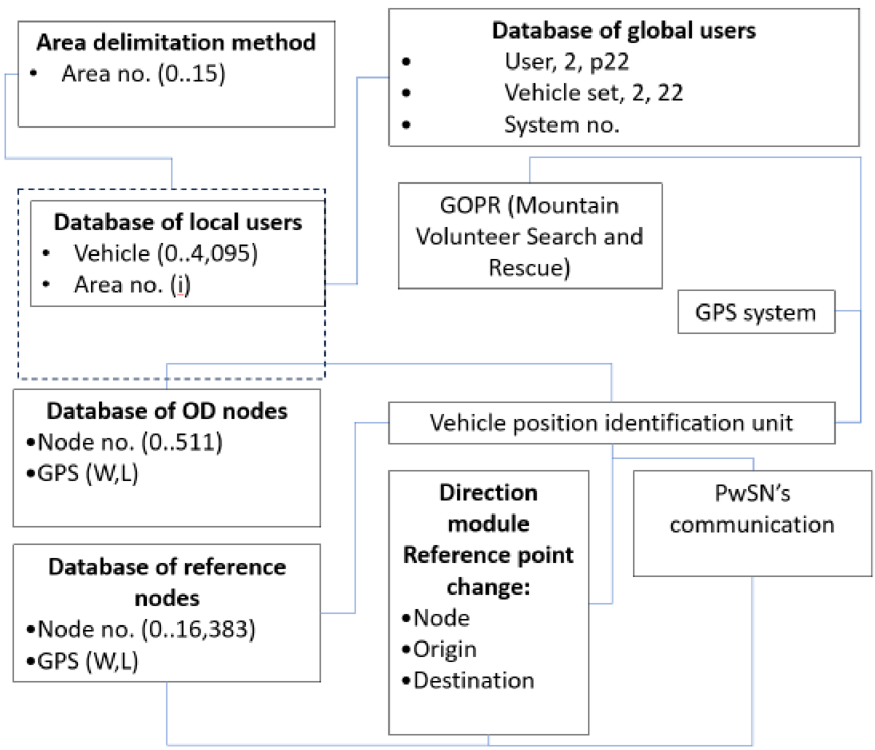

Fig. 15. Simplified block diagram of the system. Source: own elaboration

6. Discussion

The assumption underlying this paper is the need for a navigation system designed for special-purpose vehicles for PwSN based on the LoRa standard. Once the research problem was defined, analyses were performed in line with this concept. The propagation of radio waves was studied in different environments: in high- and low-rise urban development, in undeveloped land, and on a mountain trail. The observations performed and the results obtained imply that both the development type and the terrain type affect the quality of transmission according to this standard. The number of factors affecting the quality of transmission is so large that, in the end, each trail should be studied separately in order to determine the optimal configuration of reference points. The studies referred to in this paper have only highlighted certain general conclusions. Reference points are understood in this context as the places where the navigation system's receivers should be installed, i.e. at a specific point on the trail. The ultimate solution proposed is to implement a special system for the optimisation of the on-trail spatial distribution of reference points based on measurements conducted using a drone equipped with the system's receiver.

As shown in Fig. 16, the drone with a model receiver on board follows the vehicle for PwSN on the trail, changing its position all the time. And for this trail, the drone determines the distribution of the optimal locations for the system's reference points where the signal quality is the best. The procedure itself is quick and simple; it boils down to saving a cloud of 3D points with transmission signal quality parameters defined. Next, using numerical methods, optima are sought in these sets, only to be correlated with the terrain. This can also be optimized during the operation of the mountain route in terms of data flow between different points. This means that the configuration on the trail would be flexible and would change as the data collected varied. The body of problems discussed in this article also concerns studying the impact of the trail slope and curvature. Although the studies performed by the authors and the results thus obtained allow certain generalisations to be made about the navigation system configuration, this still requires tests to be conducted directly on the trail. The mountain environment is a complex structure, where heterogeneous terrain relief is accompanied by non-uniform vegetation, distribution of watercourses and bodies of water. What one should consider besides these characteristics of the 3D space of the environment in which the system proposed is supposed to operate is the infrastructural conditions specific to the trail. It is for the complexity of a traffic scene with a special-purpose vehicle intended for PwSN that these problems are so difficult to tackle. With reference to the research performed by the authors, the rationale behind the implementation of the solution proposed has been defined, and its advantages and disadvantages described. Its main advantage over other systems is resistance to local specifics and weather conditions. Compared to the GPS and inertial systems, the system in question offers different features. It is also more secure than visual systems.

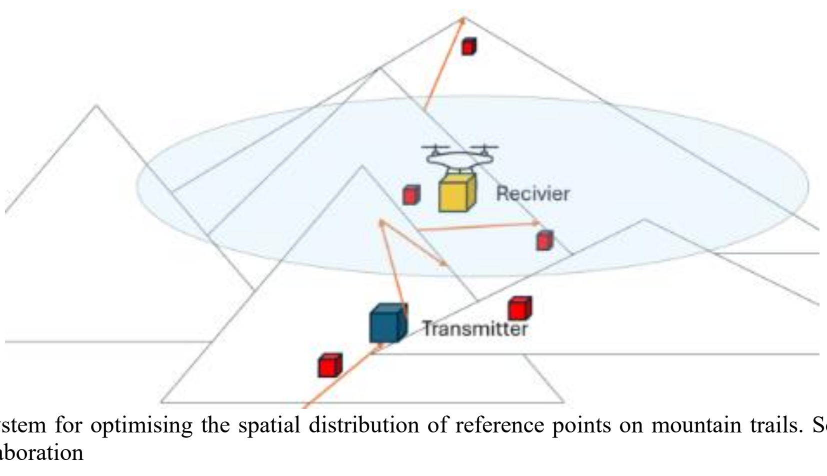

Fig. 16. System for optimising the spatial distribution of reference points on mountain trails. Source: own elaboration

7. Conclusions

The results obtained throughout the research imply that the solution proposed can be considered as a viable alternative in cases where the GPS signal is either unavailable or considerably disrupted, while its additional features provide relevant forms of support to people with special needs, navigating through mountainous terrain using special-purpose off-road vehicles. There are numerous other aspects which need to be discussed in the context of the system in question. As a result, we received information on the functionality of our system in various terrain conditions, installation and configuration of tele transmission devices. The recorded data relates to specific locations and infrastructure parameters identified in those places. We have presented numerous empirical data in selected contexts in a large collection of graphic illustrations. Of course, we have not exhausted all aspects of the problem, we have presented the most typical ones. For example, we haven't performed extensive testing of transmission errors. However, the small amount of information transmitted in the system shouldn't play a significant role here. This is true for simple mountain trails. There are several unusual configurations in Poland that would require such analysis, where several or even dozens of trails are used in a small area.

One of them is the problem of passing points on mountain trails. Now, the process of interaction between hikers, or even MTB cyclists moving in different directions, is of little importance, which results from the relatively small breadth of both hikers and mountain bicycles. However, the vehicles intended for PwSN are significantly wider, up to one metre in width. This requires that a passing scheme is created and probably that special infrastructure elements are built on the trails envisaged for this purpose, also to address the needs of this system.

Another problem is the accessibility of trails for PwSN along with their vehicles. In some cases, over a dozen or so kilometres of trails generally accessible for PwSN, there can be one or several sections with protective chains or with extreme slopes that can only be negotiated on foot. This means that without dedicated elements of infrastructure, the accessibility of the best sections of mountain trails for people with special needs will be limited, not to mention that, at this point, it is uncertain what kind of infrastructure elements there should be to enable vertical position changes on difficult trail sections.

Another problem not analysed in this article is the cybersecurity related to the safety of PwSN on mountain trails. A LoRa-based navigation system is not secured well enough against cyberattacks, especially malicious ones. At the same time, it is more a matter of safeguarding the system itself and not the vehicles. What also matters security-wise is the way in which the receivers are positioned and installed, and in what kind of enclosures (theft protection).

Another matter at hand is the capacity of trails and other technical infrastructure, relevant where hiking and cycling traffic streams interchange on the trail, especially on narrow parts, where congestion can be expected. While congestion is not a problem at low traffic speeds, it does become a problem when rapid evacuation from the trail is needed. This would require adequate evacuation procedures to be developed.

The hypotheses formulated in this article (1 through 11) should be further refined. They have been provided herein regarding the traffic of special-purpose vehicles for PwSN in terms of mountain trail profiles. The latter factor can locally alter the characteristics of the traffic of these vehicles to a considerable extent.

Another problem to be analysed is that of environmental conditions. Many mountain areas are organisationally linked with national parks, which requires analyses of the potential for installing such systems in these territories also from this angle. Yet another aspect to consider is the availability of a system aligned with a given standard in different countries. This entails the necessity of at least three development versions of the system to be created in order not to restrict the end user market. As concluded in the course of the studies in question, the relative elevation in the receiver-transmitter system is indeed important, opening a broad field for further research on different antenna setups and types, including in relation to the design of the vehicle for PwSN. In the mountains there are significant elevation changes that can cause signal loss.

And finally, both the queuing theory and traffic micro-simulation make it possible to study individual features of the navigation system intended for special-purpose vehicles for PwSN under laboratory conditions. Moreover, the system's reference receivers cannot be installed at locations offering the best transmission parameters by taking solely the system's communication requirements into account, since in high mountains, there can be several metres of snow in winter, while ponds and watercourses tend to form in spring. As implied by this summary, the problem discussed in the paper is difficult to solve and there is a very practical context to it, including, for example, the system operation aspect. Even though the LoRa technology is characterised by low energy consumption and the reference receivers can run on a single battery pack for many years, they still need to be replaced every now and again, which poses yet another problem. However, it can be solved by building an auto-diagnostic function into the system.

White was studying the subject matter in question, a queuing theory-based system was taken into consideration for the navigation system being designed. A queuing system is an intentionally designed organisational and functional structure intended for the execution of specific tasks. Such a system comprises the following components: waiting room, also known as a queue, service points, also known as (service) channels, input stream, and output stream. Navigation systems are organised in the same manner as any other queuing system. The queuing theory, as it is commonly referred to, deals with analysing objects arriving at service points and those which are (typically) queuing to be served in the waiting room. How queues are created upstream service points depends on the infrastructural and organisational limitations of each system, if traffic (demand) structures are known. This makes it a system where attempts are made to balance demand with supply. These systems are essentially stochastic (based on an assumption that various random processes are observed in these systems). Therefore, the rate of customer inflow is assumed to be a random variable. Given the foregoing, the infrastructure and organisation of the service points provide a certain theoretical level of customer service. However, if they arrive in a non-typical manner (e.g. faster than usual), there are queues forming in the system. If they arrive more slowly, the service cost becomes inflated. Queues always pose a problem in transport systems, to a greater or lesser extent. In the first place, this problem is related to the time lost. The formation of queues is due to the randomness of the request submission process and often also to the service process randomness.

Another assumption made for the studies of the system in question was to build a micro-simulation model for several chosen routes in the mountain ranges of Góry Świętokrzyskie, Karkonosze, and Bieszczady. The Karkonosze mountain range is particularly interesting in the sense that it borders high mountains and yet most of its trails are accessible, and most of them also to special-purpose vehicles designed for PwSN (unlike, for example, in the Tatra Mountains). The characteristics of most trails in the Bieszczady favour travel by means of special-purpose off-road vehicles (Fig 15a). To analyse this aspect, the PTV VISSIM traffic micro-simulation programme was used. Just like in VISUM. Analyses from a process perspective can be performed in the Flexsim environment or Simio. Two test areas were built using this solution for purposes of analysis of the navigation system intended for special-purpose mountain vehiclesThe Świętokrzyskie Mountains are a very important range in this respect, located centrally in Poland and with low elevations (Fig. 15b). The Authors have tests available on request, as even small elevations, combined with arcs, significantly affect the signal strength in the system.

a) b)

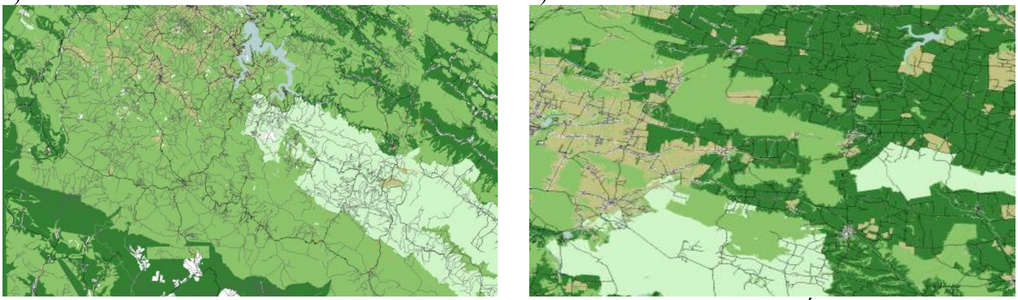

Fig. 15. Examples of system simulations for the mountains of: a) Bieszczady, b) Góry Świętokrzyskie; source: DLR, SUMO Source: SUMO environment by DLR

Recently, the system has been expanding, and we have also added eye control for the driver based on our proprietary eye tracker (Staniek et al, 2025). Thanks to this, we can study the operation of the navigation system in combination with selected behavioral factors of the vehicle driver. It is also worth mentioning that such a navigation system can be implemented in conjunction with dedicated trip planners. It can be adapted for this purpose a multimodal travel planner based on a heuristic approach to support local authorities in urban traffic management. (Sierpiński et al., 2017). This planner was also implemented by our team. Similarly, we developed a digital twin for this vehicle. Here, we can explore the connections between aspects of the navigation system and the vehicles' actual behavior on a mountain trail. (Staniek et al., 2026).

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