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Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area – a case study of the Bielany campus at the Nicolaus Copernicus University in Toruń

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Abstract. In order to assess or determine the overall quality of the surrounding geographical environment, it is necessary to measure selected factors that directly or indirectly affect its condition. The aspects to be monitored include i.a. air pollution levels, surface water purity, soil erosion rates, as well as night sky light pollution, a phenomenon increasingly often observed with the unaided eye. To collect data on the night sky brightness on a regular basis, a remote measuring device was designed and constructed using specialised electronic components, wireless communication, programming code, a high-sensitivity digital light data logger and custom-made programme code. LPWAN networks, including LoRa technology, were developed to support a number of mobile devices where long wireless operation is a priority. To determine the potential use of LoRa technology, as well as to plan the target locations of network access gates (gateways) and the deployment of measuring devices for the collection of environmental data, tests of signal coverage and signal visibility, including measurements of its strength, were carried out in a selected, compact part of the city of Toruń. The paper presents the results of research on the visibility of the LoRa network in a built-up area, such as a university campus, using antennas of two different lengths. The obtained results can be used to design distributed measurement networks in areas with varying density of buildings.

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Contents:

1. Introduction

Through technological development and successively implemented industrial solutions, man has a significant impact on the surrounding natural environment in all its dimensions. Along with the global development of civilisation, the natural space for the free functioning of organisms and the natural cycle of nature has been limited. Most of the environmental compartments (including the most perceptible ones – air, soil and water) have already been polluted to varying degrees, which can be observed both in the vertical and horizontal gradients, both in urban areas and outside their formal borders and outside human settlements (Lawrence et al., 2004; Qadri et al., 2020; Arsovski et al., 2018).

Each of the diagnosed factors negatively affecting the natural environment should be subject to long-term measurements and targeted monitoring. This helps to understand the specifics of the analysed phenomenon, its impact on the environment, as well as to assess the directions and strength of its spread, and to determine the spatial extent and limits of its occurrence. Such measures help to ultimately create effective mechanisms for limiting and counteracting these negative factors. There are many commonly used methods of measuring phenomena observed in the natural environment. These include measurements made with the use of manual recording devices – detectors, in which the measured value is shown on a display or saved on a memory device (Hänel et al., 2017; Jechow et al., 2019; Ścieżor et al., 2010). There are also more automated measurement methods carried out by means of distributed sensors placed at the target location and remotely transmitting data packets to a server specified in the transmission protocol. In the latter method, measurements are performed with the help of wireless data transmission technology and multidirectional device communication, which is an important element of the Fourth Industrial Revolution (Industry 4.0).

The objective of this work was to analyse and visualise the visibility of the LoRaWAN network in a built-up area using various hardware configurations – antennas of different lengths. The field explorations were aimed at investigating the quality of the LoRaWAN network signal in the Bielany campus, Nicolaus Copernicus University in Toruń, which reflects the typical traditional, dispersed urban development, and therefore can serve as a good testing ground for assessing its applicability for urban areas.

2. Study area

Nicolaus Copernicus University (NCU) in Toruń is the largest university in northern Poland. It is also one of the best universities in the country, which in 2019 was awarded the prestigious status of a research university as part of the "Excellence Initiative – Research University" programme. The NCU centre is distinguished not only in terms of academic potential, the variety of courses offered or the number of students and graduates, but also by the fact that most of its units are located within the university estate in Bielany (Popławski, 1982), which has been designed from scratch, inspired by the American concept of campuses (Fig. 1). This is the location of more than half of the faculties of the Toruń part of the University, the central administration (rector's office), the Main Library,

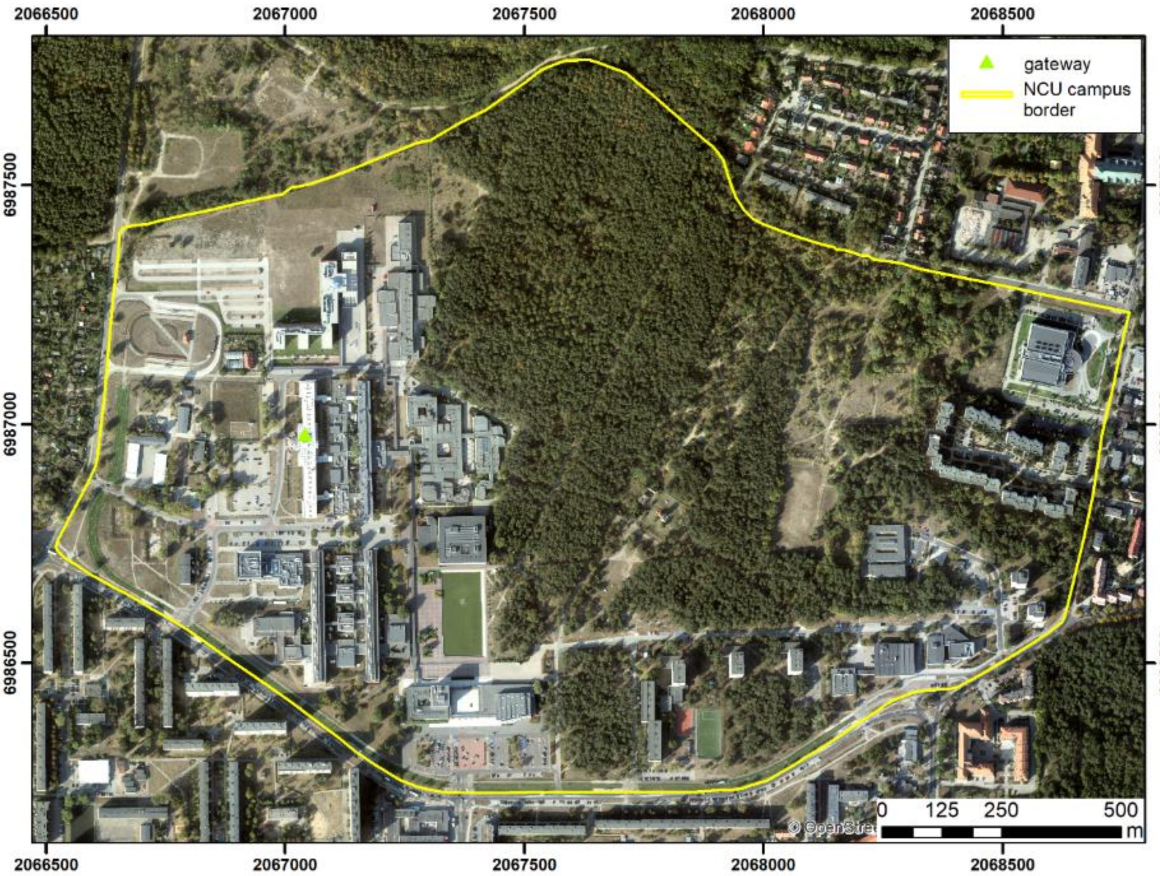

Fig. 1. Orthophotomap of the Nicolaus Copernicus University campus in Toruń with the location of the access gateway and boundaries of the area.
Source: Authors' own elaboration.

educational facilities, research units, university centres, auditoria, student dormitories, and university staff accommodations, and this is also where student life and sport activities are concentrated (Kunz, 2012). The NCU campus was included in the register of monuments by the Kujawy-Pomerania Provincial Heritage Monuments Protection Office in May 2019, which proves its exceptional urban and artistic values.

The height structure of the campus is distinguished by the dominance of 2-storey buildings with a low, fully functional ground floor, but with an atypical, non-standard storey height (about 3.5 m); the Rector's office, consisting of as many as seven levels, is the highest building in the campus.

3. Material and methods

Wireless data transmission technologies are increasingly used during the monitoring of different elements of the natural environment. The use of wireless communication enables measurements of specific parameters in many previously inaccessible locations, including non-urban areas, their viewing and reading at any time, and the inclusion of a given location in the measurement network.

3.1. Wireless data transmission technologies

The available methods of wireless data exchange include well-known technologies such as Wi-Fi, Bluetooth, and GSM (from 2G, through 3G, 4G, to already widely popular 5G). Each of the above mentioned solutions has defined technical and quality parameters, specific technical and infrastructural requirements, as well as limitations in their application (Bogacz & Krupanek, 2013). In terms of remote environmental measurements, the most important characteristics of wireless technologies include the transmission/communication range and power consumption affecting the operating time of a device on a single power supply set. Bluetooth and Wi-Fi technology has a range of several dozen metres and is ideal for sending data over short distances. The commercial GSM network, which has a much longer range, can be used to send data over long distances (Tomaszewski, 2020). Wi-Fi and GSM networks are characterised by the ability to transmit large amounts of data, but the consequence of this process is higher power consumption during data transmission (Chaładyniak, 2011). In terms of accommodating different needs and expectations, which relate to both cost reduction, energy efficiency and long-distance transmission, and supporting cloud logging, LPWAN (Low Power Wide Area Net-work) proved to be the best choice for data transmission, with Sigfox, LoRaWAN and NB-IoT being the most popular standards (Mikhaylov et al., 2018). Each of these standards is characterised by different parameters and specific applications.

Installation of an LPWAN network constitutes part of a larger research project aimed at determining the light pollution of the night sky in Toruń, which is measured using an original, in-house prototype of an autonomous, low-cost measurement set. Forty repeatable devices were constructed, which will form a "distributed measurement cloud" and will ultimately enable monitoring of the entire area of a medium-sized city of approximately 100 km2. Different data transfer technologies were considered for this part of the project, but after analysing their potential possibilities, LoRa technology, which is part of the LoRaWAN standard (Piątek, 2018), was selected.

The LoRaWAN standard is a long-range radio MAC (Medium Access Control) communication protocol that allows devices to connect to the network with low power consumption (Semtech, 2015). LoRaWAN is one of the solutions used for communication of Internet of Things (IoT) devices, which supports the idea of Smart Cities (Lozynskyy et al., 2021) as part of Smart Environment and an element of Industry 4.0 (Turčinovićet al., 2020). It is used in many applications, not only in the field of modern traffic, logistics or environmental solutions, but increasingly also for the management of entire housing estates or large settlement units – towns, cities and agglomerations (Gaël et al., 2019; Lorabit, 2019a: Ragam & Nimaje, 2019). LoRa (Long Range), in turn, is a wireless communication technology programmed for the LoRaWAN standard. In terms of product positioning, LoRa technology fills an existing niche between widely available technologies, such as Wi-Fi, Bluetooth and LTE, and stands out in terms of both reduced operating costs, possible data transmission distances and, above all, energy efficiency due to low requirements for high transmission power (Fig. 2).

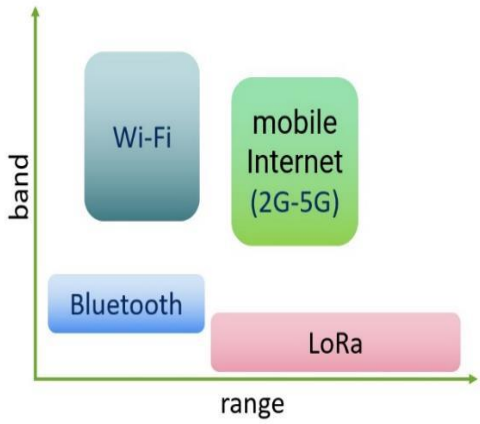

Fig. 2. Schematic comparison of the selected parameters of the wireless technologies.
Source: Authors' own elaboration.

3.2. Methodology of LoRaWAN network signal measurements

The first step in the process of determining the LoRaWAN network signal visibility on the NCU campus in Toruń was to find the potential and optimal, in terms of key parameters, location of the external network access gateway (Karpińska & Kunz, 2021). Ultimately, the most spatially advantageous and accessible location turned out to be the observation deck located on the roof of the two-storey building of the Faculty of Earth Sciences and Spatial Management, Nicolaus Copernicus University (Fig. 3), which is an integral part of the Meteorological Observatory.

The access gateway of the American company Multi-Tech Systems Inc. together with the external antenna was installed in a permanent way at an

Fig. 3. 360° panorama from the observation deck of the Faculty of Earth Sciences and Spatial Management NCU in Toruń.
Source: Authors' own elaboration.

altitude of 71 m a.s.l. and at the same time 15 m above the ground. Geographic coordinates of the installation site are as follows: 53°1'17.23"N and 18°34'6.45"E. In the horizontal surroundings of the communication gate (see Figure 3), there are university buildings of a similar height, and in the farther perspective – a multi-family housing estate with high buildings (mainly 11-storey tower blocks) in the south, recreational plots and the airport of the Pomeranian Aero Club in the west, a single-family housing estate in the north, and so-called Lasek Bielański (Bielany Forest), i.e. a dune foreland covered with mature coniferous forest stands.

The network signal visibility tests on the NCU campus in Toruń were carried out using two different antennas with a length of 34 and 82 cm (Fig. 4). In the developed assumptions of the designed research, the selection of an appropriate antenna length is an important element in determining the signal coverage, but in densely built-up areas the importance of this parameter is reduced in favour of other variables. The mDOT Box tester from Multi Tech Systems Inc. was used to test the visibility of the LoRaWAN network (Fig. 5). The device is of compact design and has several measurement modes that facilitate data collection and its correct positioning in the geographical space.

To verify the visibility of the signal, the tester uses the single sweep mode, in which the unit availability to the LoRaWAN network is checked for a selected transmission power and a length (size) of the generated message. The device also has a built-in GPS module, which facilitates the spatial location of measurement points. According to the manufacturer (MultiConnect 2020; Multi-Tech Systems 2020), the following information is displayed in one data frame during the reading:

- identifier (ID) of a measurement point,

Fig. 4. External communication gateway of the LoRaWAN network with 34 cm (left) and 82 cm (right) antennas.
Source: Authors' own elaboration.

Fig. 5. Compact LoRaWAN mDOT tester from Multi Tech Systems, Inc. used in the field tests.
Source: Authors' own elaboration.

- location of a measurement point (XY),
- number of a communication gateway, the access to which is being checked,
- factor determining the quality of the signal, so-called margin,
- normalised indicator of received energy, both in terms of signal and noise, so called RSSI (Received Signal Strength Indication),
- Signal to Noise Ratio, so-called SNR.

Of the last three above-mentioned key pieces of information contained in the data frame, the margin factor was selected for further analysis and preparation of LoRaWAN signal visibility maps. It represents the quantified quality of the connection between the tester and the access gateway, with values ranging from 0 to 30 dBm, where higher value indicates better quality of the established communication. In terms of functionality, the best – very good (expected) connection between devices is obtained when the value of the margin factor ranges between 20 and 30 dBm. The value of 12–20 dBm indicates good quality of the signal, and 0 dBm or not value at all translates to an inability to establish a connection with the access gateway (Multi-Tech Systems 2020).

The quality of the LoRaWAN network signal on the NCU campus was determined at points forming an irregular grid covering the entire study area and its immediate surroundings. Measurements were conducted at a height of 1.5 m above the ground. The intervals between the measurement points ranged from a dozen to several dozen metres and covered all places available for pedestrian exploration, i.e. roads, paths and traffic routes, squares, car parks, lawns and urban green space. The points were selected in such a way as to make it possible to determine the availability of the LoRaWAN network at any location, even in so-called building shadow, which is often the case in densely built-up areas or tower blocks. It was assumed that the quality of the transmitted signal is affected by spatial barriers, i.e. buildings of any cubic capacity (Fig. 6), plantings,

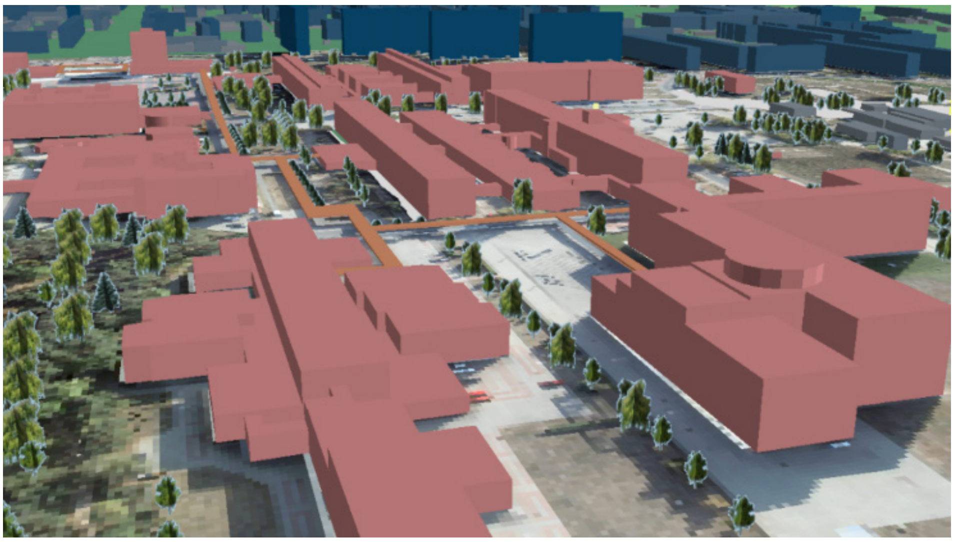

Fig. 6. Three-dimensional visualisation of a part of the NCU campus in Toruń viewed from the south-western side; red colour indicates University buildings, and blue colour indicates all buildings outside the campus.
Source: Authors' own elaboration.

natural visibility obstructions – slopes, cliffs, as well as the increasing Euclidean distance from the access gateway.

4. Results

After collecting the necessary field measurement data, the LoRaWAN signal visibility analysis was performed using ArcGIS (Esri) and the 3D Analyst extension. In the interpolation process, the Spline method was used, with the actual horizontal and vertical extent of the NCU campus building development used for each period of the analysis. The whole analytical process was performed for transmitting antennas of two different lengths – 34 cm and 3 dB gain (Fig. 7) and 82 cm and 5.8 dB gain (Fig. 8).

Figure 7 shows the availability of the LoRaWAN network demonstrated using the shorter of the communication antennas. The strongest network signal was obtained in areas directly visible from the observation deck. There is clearly no signal (red area in this figure) in areas directly behind buildings, in their so-called shadow, i.e. in places where direct, straight-line visibility between two points is not possible. Figure 8 shows the visibility of the LoRaWAN network when the longer antenna is used. In this case, a significantly higher coverage of the NCU campus area was obtained, if not very good, then at least good signal of the tested wireless network, and the recorded minimum exceeds 10 dBm. There are still places, directly behind the buildings, with weaker signal reception, but they are of much smaller sizes than in the first case.

The size comparison of the areas with no LoRaWAN signal is presented in Figure 9. In the case of the shorter antenna, the likely area without the LoRa network coverage is as much as 31% of the entire campus, while for the longer antenna this value drops to only 2% of the campus area.

The spatial range of the LoRaWAN signal when using an antenna with a gain of 3dB gain (shorter)

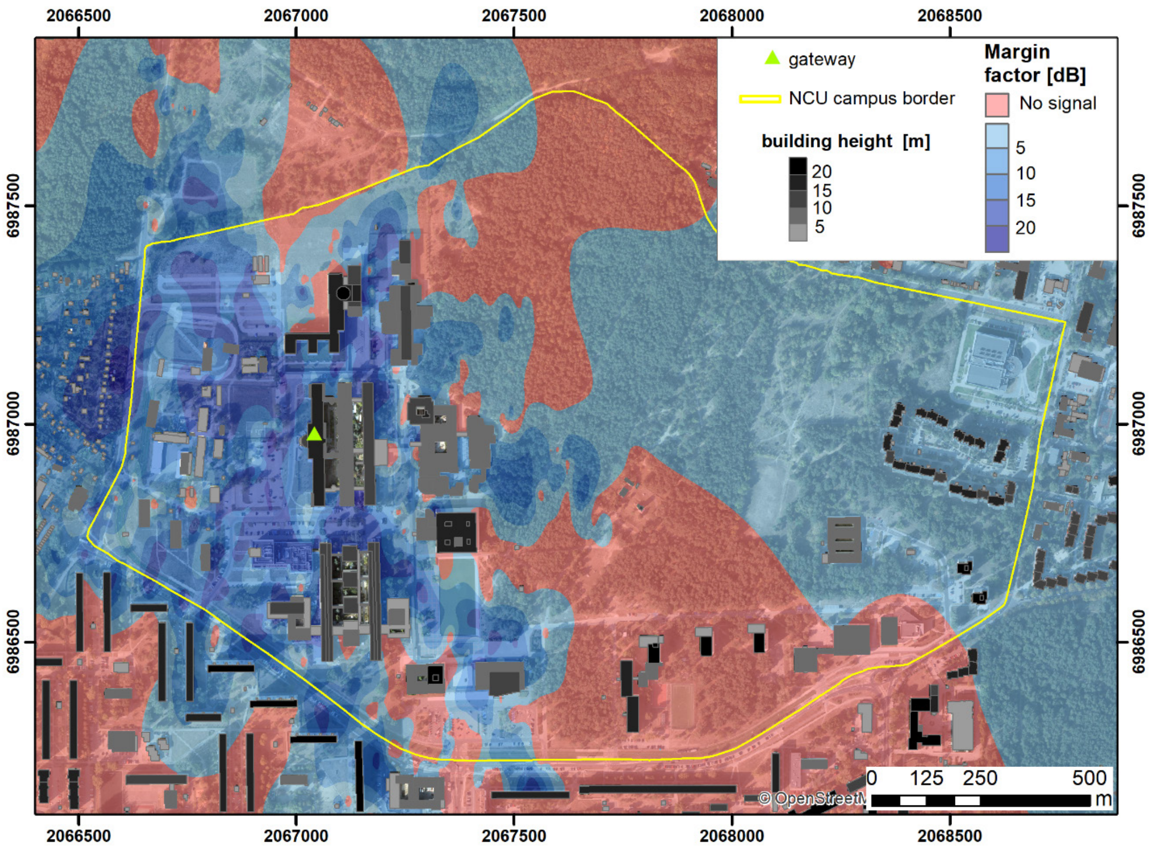

Fig. 7. Visualisation of the LoRaWAN network signal quality on the NCU campus using a 34 cm long antenna.
Source: Authors' own elaboration.

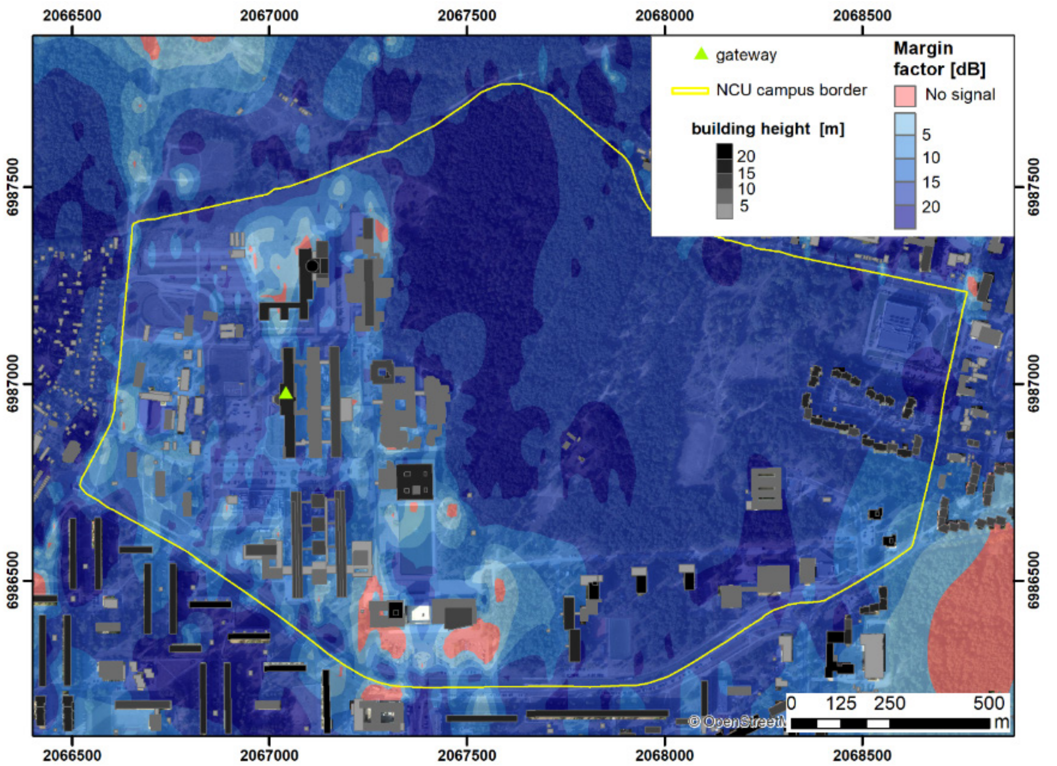

Fig. 8. Visualisation of the LoRaWAN network signal quality on the NCU campus using a 82 cm long antenna.
Source: Authors' own elaboration.

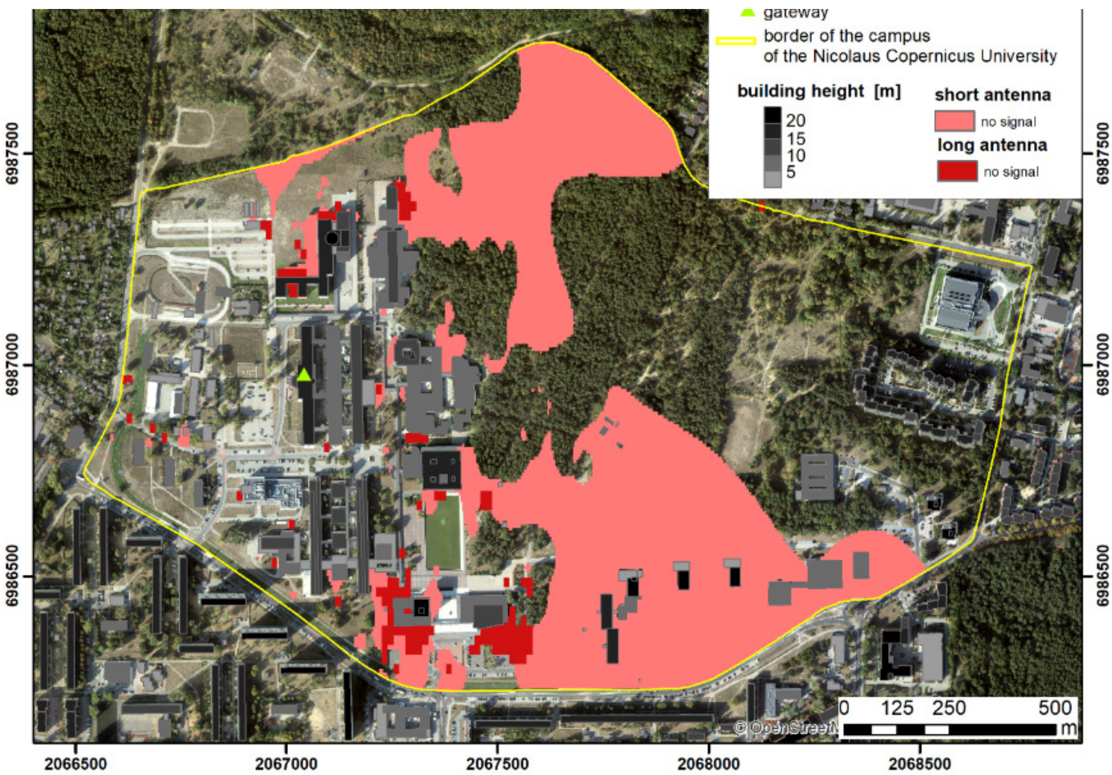

Fig. 9. Campus area with no LoRa signal for the shorter (34 cm) and longer (82 cm) antenna.
Source: Authors' own elaboration.

and 5.8 dB gain (longer) differs significantly. In built-up areas, the achievable range for the shorter antenna is approximately 1 km. On the other hand, the longer antenna enables data transmission from a distance of over 4 km, which significantly increases the possibility of using this infrastructure in built-up areas. Due to the much greater range obtained in the second case, in order to properly visualise the LoRaWAN network visibility, it was necessary to collect measurement data from a much larger area. As in the previous analysis, the data were interpolated using the Spline method, and the results are presented in Figure 10. The study shows that the network signal covers a large area, and a significant limitation are terrain elevation differences, which increase to the north and east from the gateway location, as well as the density and height of buildings. The opposite situation is observed when analysing the visibility of the network to the south and west, where the density and height of buildings is much lower. The process of signal propagation is also enhanced by the presence of areas with low vegetation and the Vistula River, rendering the areas free of taller elements of the urban fabric. This example perfectly illustrates both the advantages and limitations of wireless networks in built-up areas.

The analysis of the effects of the distance from the communication gateway on the signal quality shows that both terrain obstacles and the increasing distance reduce its strength and visibility. For areas close to the transmitter, on the other hand, increasing distance is less important than the size and volume of the object obstructing the signal. As the linear distance increases, the impact of the building height on the signal quality also increases.

In order to verify the results of the above analysis, Fig. 11 presents terrain profiles constructed between the point where the access gate is located and subsequent measurement points. The analysis covered the points where excellent network quality was observed for both the longer and shorter antennas (profiles B and C – blue line), the points where in both cases no LoRaWAN network signal was observed (profiles A and E – red line), and cases where the signal was observed for the longer

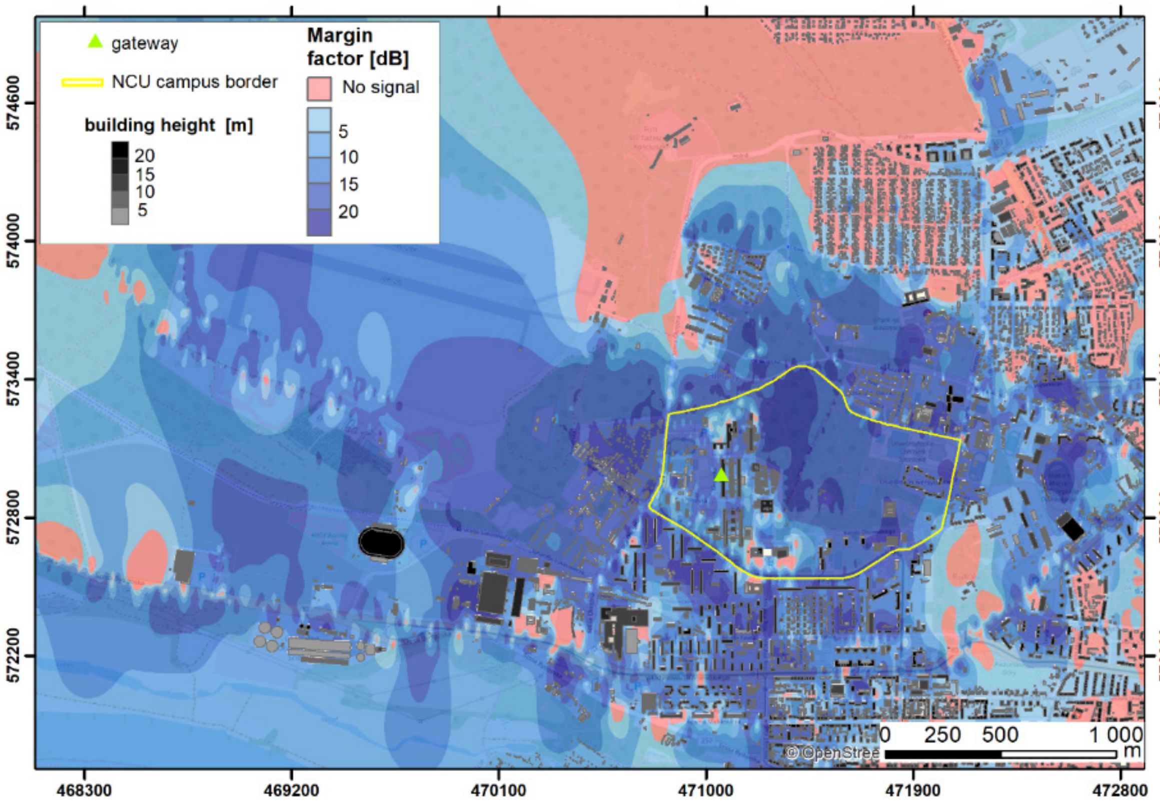

Fig. 10. Interpolation of measurement data for a larger area using a 82 cm long antenna.
Source: Authors' own elaboration.

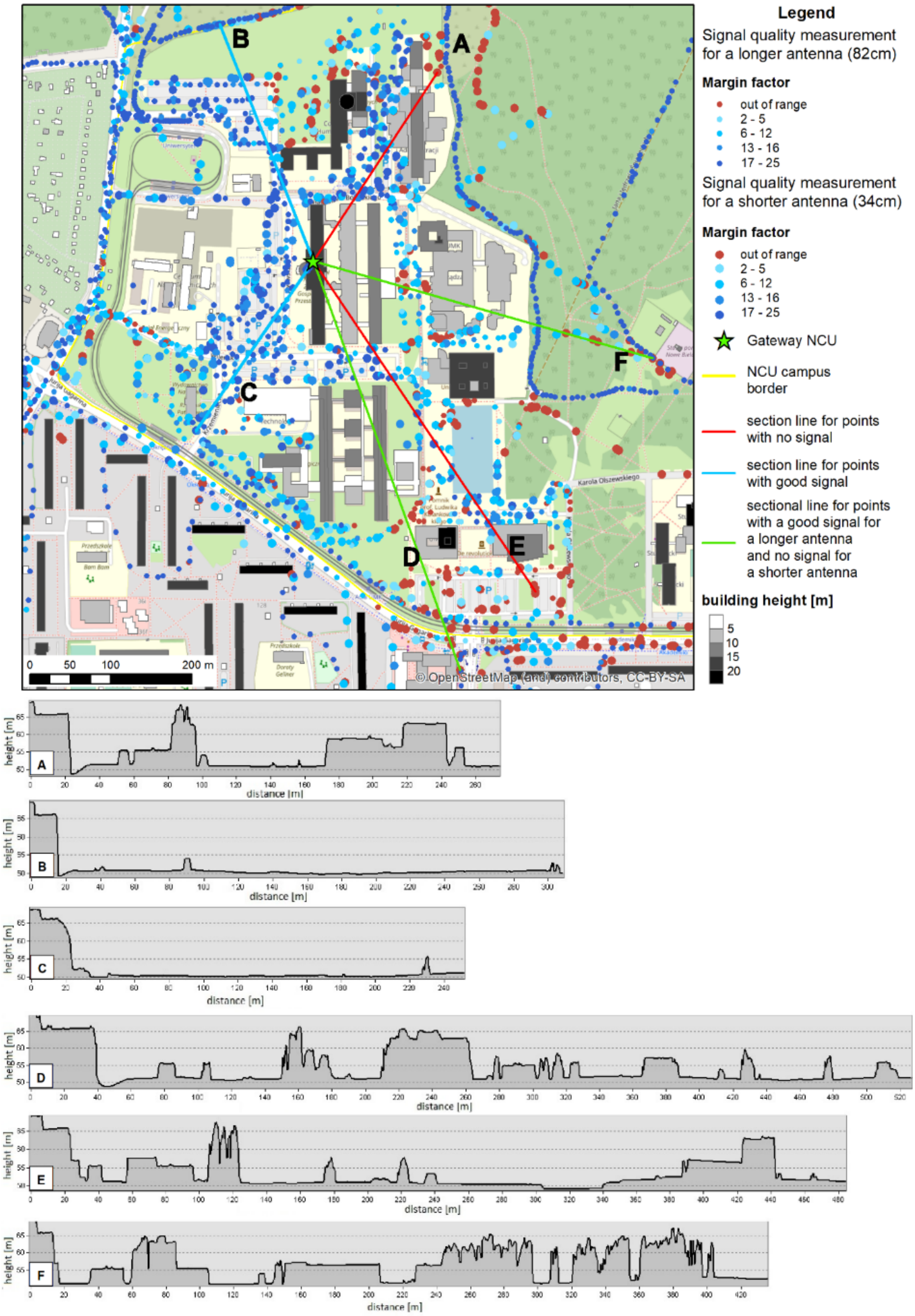

Fig. 11. Location and visualisation of terrain cross-sections showing obstacles in the path of the LoRa signal to the measured measurement points.

Source: Authors' own elaboration.

antenna but not for the shorter one (profiles D and F – green line). The points were selected within the network coverage area with the shorter antenna used.

The analysis of the selected cases shows that for profiles B and C created for points with good signal quality, there are no high terrain obstacles on the way that would prevent signal propagation. In the case of profiles A and E, created for areas with no network coverage, there are numerous terrain obstacles and, what is important, high buildings with considerable cubic capacity are located near the measurement point. Profiles D and F are characterised by a large number of terrain obstacles, however, there are no large-size buildings near the measurement point. The network is not available there if an antenna with a lower gain is used. In addition, the F profile runs through the wooded area, which proved to be disadvantageous for the signal from lower gain antennas. The analysis proves the prior assumptions as the differences between the selected equipment are clear in the presented material. When planning the installation of a network, it is necessary to carefully choose the structural elements of the technology used.

The presented research shows the advantages and limitations of using a wireless network in urban areas. The signal propagation of the selected LoRaWAN wireless network is very limited in areas with high-rise buildings. However, there are areas where even a small infrastructure of this type of technology can successfully provide monitoring of selected environmental parameters. To achieve such an effect in densely built-up areas, it is necessary to increase the density of network infrastructure elements.

With the intensive spatial development of urban areas and the planned construction of further edifices and facilities, the availability of the wireless network signal will also significantly deteriorate. This will result in increased areas of non-surface availability, where it will not be possible to connect any measuring device to a communication gateway of the LoRaWAN network. In such a situation, it will be necessary to install additional access points, which will significantly increase the operating costs of the implemented solution and cause further densification and overlapping of signals of all wireless technologies used in a given area, not to mention their potential negative impact on interference with other electronic devices (Politański et al., 2016; Zmyślony, 2006).

5. Discussion

Nowadays, even when we use only visual rather than instrumental observation methods, we notice the progressive deterioration of the natural environment around us. Distributed monitoring of selected environmental parameters is becoming increasingly common and helpful due to its spatial scope. Targeted measurements are increasingly often carried out using wireless recording systems and technological processes of data transmission over long distances. The Nicolaus Copernicus University campus proved to be a good testing ground for such an experiment, as it is an example of a multifunctional heterogeneous urban area with different characteristics and the presence of all typical components of the urban fabric, from low, through medium to high dispersed and compact building development, as well as numerous trees and characteristic small landscape architecture.

The conducted tests confirm the prior assumptions that the most important barriers for the wireless network are large buildings, which at the same time had a significant relative height in relation to the height at which the access gateway antenna is located. Single trees or larger clusters of trees can also reduce the quality of the received signal, but they do not cause its total disappearance.

An inevitable consequence of the development of urban areas, especially those attractive for housing, is the increasing density of building development, which slowly fills every available space in a modern city. Furthermore, when older buildings are demolished, they tend to be replaced by taller structures and the neighbourhood thus becomes more compact. Studies have proven that the density of building development affects the quality and availability of the wireless network and the range of data transmission. To obtain the same signal availability as before the expansion of selected areas, it will be necessary to launch additional access points, which will significantly affect the costs of the undertaking, and to install a fully operational wireless network supporting a “distributed measurement cloud" of any set of sensors. Unfortunately, this is a negative consequence of the intensification of urban expansion, but on the other hand also a new field for targeted, interdisciplinary research in this field.

The results of the targeted experiment conducted on the NCU campus will be used in designing a LoRaWAN wireless network throughout Toruń. On the basis of these results, potential locations of access points will be selected so as to significantly minimise their number, while increasing the number of connectable devices covering a larger area. In the near future, such a network, consisting of the already prepared forty twin sensors, will be deployed in Toruń under the assumption that all important land cover/land use categories exist in the vicinity of a selected point. These operations will also make use of experience gained during the data acquisition process in the summer season (Karpińska & Kunz, 2019), as well as throughout the year (Karpińska & Kunz, 2020) using standard, hand-held SQM loggers. Measurements conducted on the basis of a synchronised cloud of recording devices will be the basis for the implementation of a project aimed at studying the level of light pollution of the night sky in Toruń over a longer period of time. These results, in turn, can be used by other researchers in determining the relationship between the effects of artificial outdoor light sources in towns and cities on the quality of life and health of their residents.

Both the construction of a wireless network based on the LoRaWAN standard and the measurement of excessive artificial light emitted at night are part of the project involving the smart city concept, being an important element of Industrial Revolution 4.0 (Industry 4.0).

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