THREE-DIMENSIONAL VISUALISATION OF SPATIALLY DISPERSED PHENOMENA ON THE EXAMPLE OF THE EDUROAM WIRELESS NETWORK SIGNAL ANALYSIS IN THE UNIVERSITY BUILDING

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Abstract: The study describes the procedure and conditions for performing geovisualisations based on dispersed measurement data obtained at specified spatial intervals. The research utilised a rarely used method of representing dispersed phenomena in the form of static three-dimensional visualisation. The work presents the procedure necessary to create a clear and cartographically effective image of a phenomenon that is not directly observable but recorded using specialised equipment. The method was tested by analysing the spatial distribution and intensity of the signal strength of the Eduroam wireless access system operating in the building of the Faculty of Earth Sciences and Spatial Management at Nicolaus Copernicus University in Toruń. The outcome is a three-dimensional model of the signal distribution of this network within selected size intervals. The results support the building administrator's decision-making processes regarding the optimal placement of internal access points. Geographic information system (GIS) software and raster applications for processing and integrating image data were used in the conducted activities. The methodological part describes data acquisition, geodatabase creation, statistical analysis, and data interpolation using spline functions and surface estimation. The development of 3D GIS tools not only enables more precise analyses but also contributes to a better understanding of the distribution of non-linearly dispersed phenomena in space. The presented method and the results of the conducted research contribute to the practical application development of 3D GIS systems.

Keywords: cartographic visualisation, 3D model, 3D GIS, Eduroam, Wi-Fi

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Introduction

The spatial environment surrounding humans is inherently complex, comprising numerous elements and variables that should be analysed across multiple dimensions. As the complexity of spatial data increases, there is a growing need for advanced modelling techniques that transcend the limitations of traditional two-dimensional cartographic tools (Zlatanova, Ghadikolaee 2015, Kolbe et al. 2024). While useful, conventional two-dimensional (2D) cartographic approaches are inadequate for representing complex spatial phenomena, especially those measured at variable geometric intervals (Olberding, Vetter 2023). Modern three-dimensional (3D) geographic information system (GIS) tools address these

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limitations by providing more realistic and detailed visualisations of spatially dispersed phenomena. These tools allow for more precise analyses and decision-making, particularly in fields such as urban planning, infrastructure management, and environmental monitoring (Gao et al. 2023). The primary objective is the operational use of the method utilising variable chromatic spheres, regularly distributed within the analysed 3D space. The research focuses specifically on the Wi-Fi signal strength in the Faculty of Earth Sciences and Spatial Management at Nicolaus Copernicus University in Toruń (FESSM NCU) as the study object. When analysing spatial phenomena, such as the distribution of inhabitants in selected areas, air pollution, or service availability, traditional two-dimensional maps can provide only a simplified image of reality.

The development of GIS technology, particularly 3D GIS, has significantly enhanced the ability to process and visualise spatial phenomena in three dimensions. This advancement has been transformative in various fields, including urban planning, environmental management, and network infrastructure monitoring, where accurate spatial data analysis is crucial. Recent research emphasises the importance of 3D GIS for visualising complex spatial relationships that traditional 2D cartographic methods fail to capture (Zlatanova, Ghadikolaee 2015, Kolbe et al. 2024). Despite extensive research in 3D GIS, the visualisation of wireless signal strength in indoor environments remains underexplored. While conventional localisation technologies often require dedicated infrastructures, Zhang et al. (2019) demonstrated the potential of using commercial off-the-shelf Wi-Fi infrastructures to develop cost-effective indoor localisation systems. However, before such localisation can be effective, there is a need for a detailed 3D map of Wi-Fi signal strength distribution. Furthermore, recent advancements in 3D Wi-Fi antenna design, such as the work by Mair et al. (2023), underscore the need for innovative visualisation tools in the field of wireless communication. Mair et al. (2023) leveraged additive manufacturing and evolutionary optimisation to create efficient, 3D antennas, demonstrating the expanding role of 3D technologies in enhancing wireless infrastructure. These studies collectively emphasise the need for more refined geovisualisation methods in 3D GIS, particularly for wireless signal visualisation in complex indoor environments like educational institutions. This study initiates a discussion on the need to develop effective geovisualisation methods to represent the 3D variability of Wi-Fi signal strength in the FESSM NCU. The proposed method involves the use of chromatic spheres regularly distributed within the analysed 3D space, which allows for a clearer understanding of spatial phenomena like Wi-Fi signal strength.

The topic of 3D visualisation of spatial phenomena using GIS is highly relevant and significant for several reasons. First, the surrounding space is multidimensional, which means that analysing phenomena in this broader perspective allows for a more accurate and realistic representation of reality (Wegmann et al. 2020). Second, traditional two-dimensional methods of spatial visualisation have their limitations, which 3D GIS can overcome. The development of information technologies, including advanced GIS systems, enables the creation of realistic 3D models that not only present data but also allow for in-depth analysis and interaction (ESRI 2024a, b). In the context of urban planning, 3D GIS systems allow for the visualisation of future changes in urban space, which is invaluable in the decision-making process. An example is the revitalisation project of the Mülheim Süd district in Cologne (Germany), where a 3D model integrated various data, such as building information (BIM), aerial photographs, air pollution data, and noise intensity (Batty 1997).

The differences between flat (2D) and 3D cartography are significant and affect the way data are presented and analysed. Flat cartography is limited to two dimensions, which hinders the full understanding of dispersed phenomena in space, especially when they have a complex spatial character. An example is the analysis of air pollution distribution in a city. In flat (traditional) cartography, the extent and concentration of pollutants can only be presented on a 2D map, which does not provide a full picture of the impact of topography and building structures on the spread of these pollutants (Turner et al. 2016). In contrast, 3D cartography allows for data visualisation in multiple dimensions, enabling a more realistic and detailed representation of spatial phenomena. Three-dimensional techniques allow for a better understanding of spatial relationships, analysis of complex structures, and simulations and forecasts in various spatial scenarios. Modelling the 3D distribution of air pollution allows for considering the impact of building height, terrain shape, and atmospheric conditions on pollutant dispersion (Fischer, Getis 2008). Additionally, 3D cartography techniques are very useful in geological data analysis. Three-dimensional geological models allow for accurate mapping of rock layers, mineral deposit structures, and underground flows. In geological studies, the use of 3D models allows for identifying potential areas for natural resource exploitation and assessing seismic risk (Turner et al. 2016). Three-dimensional cartography is also used in urban planning, where 3D city models enable simulation and analysis of various development scenarios, considering their impact on landscape aesthetics, composition with other elements, and access to public space (Batty 2013).

This topic is particularly important in the context of contemporary challenges faced by humanity, such as urbanisation, climate change, and the management of increasingly diminishing resources. Three-dimensional GIS has the potential to become a key tool supporting decision-making processes in many fields, from crisis situations through spatial planning to modelling complex processes occurring in the natural environment (Gold 2013). Therefore, the development and implementation of effective methods of 3D visualisation of spatial data are an important element of modern cartography and a challenge for geoinformation sciences.

Another crucial aspect is the ability to model natural phenomena and determine their impact on the environment (Karpińska, Kunz 2023, Zboralski, Kunz 2024). For example, 3D modelling can be used to determine the impact of wind farms on bird migration, which is difficult to capture using only two-dimensional tools. In coastal areas, such visualisations can help plan sustainable development considering underwater topography, local vegetation, and long-term forecasts regarding the impact of human pressure on the natural environment. Three-dimensional GIS is used in managing technical infrastructure such as power grids, water supply networks, or access networks. In studies on high-voltage transmission networks in Tunisia, their 3D representation allowed for realistic visualisations and effective management of all data, processes, and variables during construction and subsequent operation (Hamza, Chmit 2022).

In the described study, the Eduroam network was chosen only as an example for conducting detailed research, and the gathered experiences and developed methodology apply to the analysis of other phenomena of a similar nature. Thanks to its versatility and advanced analytical capabilities, 3D GIS is now an invaluable tool in modern spatial management.

The global Eduroam network (education roaming) is an initiative aimed at providing secure wireless internet access for users associated with academic or research institutions. It originated in Europe and gradually expanded its coverage to other continents, becoming a global federated service. The main goal of this initiative is to enable students, researchers, and university staff to obtain wireless internet access on campus and at other academic centres using their home institution's login credentials (Florio, Wierenga 2005). The concept of Eduroam's creation and development arose from the growing need to provide secure and reliable internet access in academic environments. With the increasing use of mobile devices, such as laptops, smartphones, and tablets, there was an urgent need to create a standardised method for providing easy Internet access that could function in different institutions and countries without the need for additional actions or installations. Eduroam meets this need by offering a unified solution that is both secure and easy to use. The service has been widely adopted and has become a standard feature in many academic institutions worldwide. Nowadays, Eduroam plays a crucial role in facilitating access to network, educational, communication, and research resources. Eduroam allows researchers to work on research projects regardless of their location, which is particularly important in the era of globalisation of science. Eduroam ensures that researchers have access to necessary resources, such as databases, scientific articles, and analytical tools, which is key to conducting high-level research. In Poland, the Eduroam service is managed by the University Computer Centre of

Nicolaus Copernicus University and the Poznań Supercomputing and Networking Centre (Wolniewicz et al. 2012). Currently, 54 institutions in 43 locations in Poland use the Eduroam service. Eduroam represents a significant step in providing secure, seamless internet access for the academic community. Its robust infrastructure, combined with stringent security measures and adaptive performance management, makes it an invaluable resource for all students, researchers, and academic staff.

The scientific innovation in this study lies in the integration of these tools to develop a novel 3D visualisation technique. By utilising variable chromatic spheres to represent Wi-Fi signal strength at various locations within the 3D model, the study offers a visually intuitive representation of signal coverage. The chromatic spheres, ranging in colour from red (strong signal) to blue (weak signal), allow for easy identification of areas requiring network optimisation, providing a more comprehensive understanding of spatial signal behaviour compared to traditional 2D heatmaps. Therefore, the main objective of the study was to examine and present available methods for 3D visualisation of spatially diverse phenomena using the Eduroam wireless network as an example, utilising GIS. The study addressed this problem by focusing on several key aspects. An analysis of the available literature on the subject of 3D visualisation of spatial data and 3D GIS systems was conducted to identify trends and technologies used in geovisualisation (Wegmann et al. 2020, ESRI 2024 a, b). A detailed methodology was developed, covering all stages of creating 3D visualisations, from the data collection through processing to the final presentation. This step included various measurement techniques and analytical procedures, as well as tools for visualising spatial data.

The practical part of the study involved conducting measurements and collecting data on the signal strength distribution of the Eduroam network in the building of the FESSM NCU. The selected example served as a real object for testing the developed methodology and 3D visualisation technologies. The collection of measurement data in the form of a geodatabase and their statistical analysis using advanced geoinformation tools such as the ArcGIS environment (ESRI) was another essential element of the study. This process included data interpolation and surface estimation, which allowed for the creation of an accurate spatial model of the analysed phenomenon (Hamza, Chmit 2022). Three-dimensional models of buildings and other objects with LoD3 accuracy level were created using Trimble SketchUp software. The integration of the resulting models with spatial data enabled the creation of realistic and accurate 3D visualisations. The final stage of the work was preparing static 3D visualisations using GIS software (ArcGIS Pro, ESRI 2024) and raster graphics editing tools (Adobe Photoshop). The visualisations served to better understand and present the spatial distribution of the phenomenon. After these activities, the obtained results were evaluated for their compliance with cartographic presentation principles and their practical usability. The gathered experiences and developed methods have potential applications in analysing other spatial phenomena, making them universal tools in modern cartography and geoinformation (Kraak, Ormeling 2010, Wegmann et al. 2020).

Materials and methods

Screening and selection of the 3D GIS software

In this study, several GIS tools were evaluated to identify the most effective platform for 3D visualisation and analysis of Wi-Fi signal strength within the FESSM NCU. These tools included ArcScene (version 10.8, ESRI), IMAGINE Virtual GIS (version 2020, Hexagon Geospatial), GeoMedia Terrain (version 16.6, Hexagon Geospatial), and Voxler (version 4.6, Golden Software). Based on a detailed assessment of their capabilities in 3D spatial data handling and interpolation, ArcGIS Pro (version 2.8, ESRI 2024a) was chosen for its advanced functionality in managing complex geospatial datasets and performing detailed 3D interpolation. This selection aligns with the findings of Biljecki et al. (2016), who highlight the need for robust software in managing indoor 3D spatial data. As a result of this comparison, ArcGIS Pro was selected for conducting the spatial analyses, and Trimble SketchUp (version 2021) was chosen to create a detailed 3D model of the FESSM NCU.

ArcScene, part of the ArcGIS suite from ESRI, is one of the most popular tools for creating and manipulating 3D data. It allows for the integration of data from various sources, such as elevation data, remote sensing imagery, and other thematic data, enabling the creation of comprehensive terrain and object models. Working with vector and raster data, ArcScene enables precise surface modelling and spatial analysis, which is crucial in creating realistic spatial models (Zlatanova et al. 2002). For example, in studies on the spatial distribution of Wi-Fi signals, ArcScene can be used to visualise signal coverage under different terrain conditions, optimising the placement of transmitters or locations for efficient use of access point signal strength.

IMAGINE Virtual GIS, developed by Hexagon Geospatial, offers advanced features primarily in raster data processing. This tool allows for accurate mapping of terrain and objects on it, which is particularly useful in the analysis of large areas and the integration of data from various sources, such as satellite images, orthophotomaps, and lidar data. Thanks to spectral and spatial analysis functions, the program is used in environmental studies, natural resource monitoring, and urban planning, where precise 3D models are essential for assessing and managing space (Li et al. 2016).

GeoMedia Terrain is an advanced GIS tool that allows for batch data processing to obtain terrain models, slope models, exposure models, and visualisation. The program is used in surveying, civil engineering, and spatial planning, where precise mapping of the surface is key for assessing terrain conditions and planning infrastructure. This tool allows for topographic analysis, especially when designing roads, buildings, and other engineering structures (Gold 2013).

Voxler, a tool from Golden Software, enables advanced 3D visualisations, which is particularly useful in presenting complex and spatially dispersed data. Voxler allows for the creation of 3D graphs, surface maps, and other visualisations that help in better understanding and analysing data. This tool is used in geology, hydrogeology, and environmental engineering for modelling and visualising complex geological structures and hydrodynamic processes (Smith 2017).

The primary methodological innovation in this study was the integration of multiple software platforms to visualise the spatial distribution of Wi-Fi signal strength in 3D. This approach combined the capabilities of different tools – specifically ArcGIS Pro (version 2.8, ESRI 2021) for spatial analysis and interpolation and Trimble SketchUp (version 2021) for detailed 3D architectural modelling. This combination allowed for a comprehensive, accurate representation of how Wi-Fi signals propagate through complex indoor environments. The integration of ArcGIS Pro with Trimble SketchUp enabled the study to visualise Wi-Fi signal strength in three dimensions, which is not widely explored in existing literature.

Assessment of wireless network performance

Assessing wireless network performance involves analysing parameters such as response time, signal strength, and the number of users. Studies conducted at various universities have shown that monitoring these parameters provides valuable information about network performance and identifies areas that need improvement. Regular monitoring and assessment help identify and resolve issues such as network congestion, interference, and insufficient coverage. A key element of network performance is the proper placement of Wi-Fi transmitters, which should be located to ensure optimal signal coverage and minimise interference. Transmitters should be strategically placed in locations, such as libraries, lecture halls, and laboratories, to ensure even loading distribution and maintain high service quality throughout the network (Candido, Silva 2023). Proper placement of Wi-Fi transmitters ensures stable and fast internet access. Improper placement can lead to 'dead zones' with weak signals and congestion in areas with high user density. Therefore, it is important to conduct regular signal analysis and measurements to optimise transmitter locations and adapt them to changing user needs.

In Poland, thanks to the cooperation of many institutions, the Eduroam service is widespread and scalable, meeting high security and performance standards. Regular performance assessments and optimisation of network infrastructure, including the placement of Wi-Fi transmitters, are crucial for maintaining high service quality in the future.

Stages of the research procedure

Spatial model of the FESSM NCU building

The first step in preparing for the analysis and visualisation of the spatial distribution of the Eduroam wireless network signal strength in the FESSM NCU was obtaining detailed architectural plans of the building. This was the primary material for preparing a 3D model (Fig. 1).

Data collection process

Collecting and processing the data on Wi-Fi signal strength in the faculty building was divided into two main substages: collecting measurement data and interpolating and statistically analysing it. The data were collected using the specialised mobile application Network Signal Info Pro, ensuring high quality and precision of measurements. The measurement process involved recording the wireless network signal strength at predefined measurement levels at vertical intervals of every 15 m (Fig. 2). Ultimately, nine measurement levels were designated, which were sufficient for surface statistical estimation.

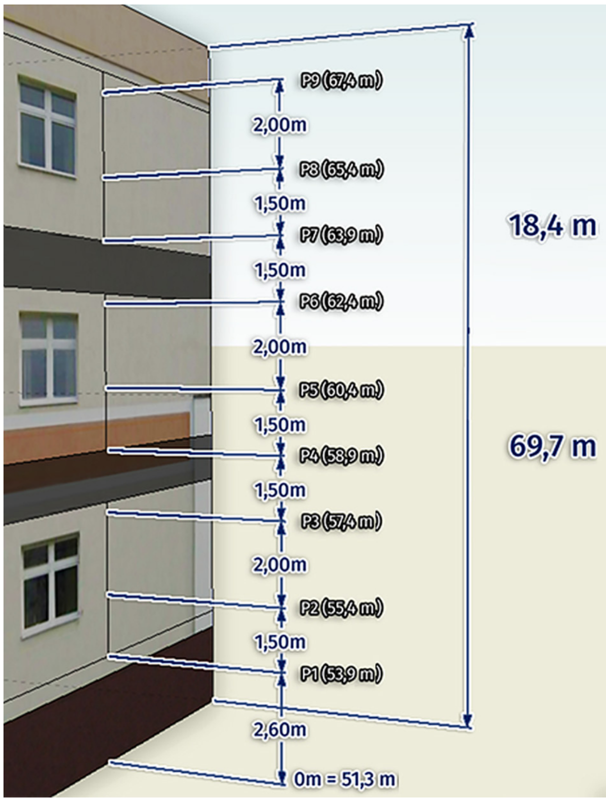

Fig. 2. Measurement levels used in the study and selected relative and absolute heights (m a.s.l.).

The next step in the data collection process was creating a file geodatabase in the ArcGIS environment (ESRI). This geodatabase served as a structure for storing all collected measurement data and additional information necessary for analysis. The geodatabase configuration included defining a coordinate system consistent with the local spatial reference system. The Network Signal Info Pro mobile application (Fig. 3) was appropriately configured to record data at regular time and distance intervals. The choice of measurement intervals (every 15 m) was crucial to ensure even data coverage throughout the building. Measurements were taken in various parts of the building, including lecture halls, laboratories, corridors, and other rooms. Each recorded point contained information about signal strength, its location, and the time of measurement. The collected data were then imported into the geodatabase, where it underwent initial analysis and verification. This process included checking data correctness, identifying and

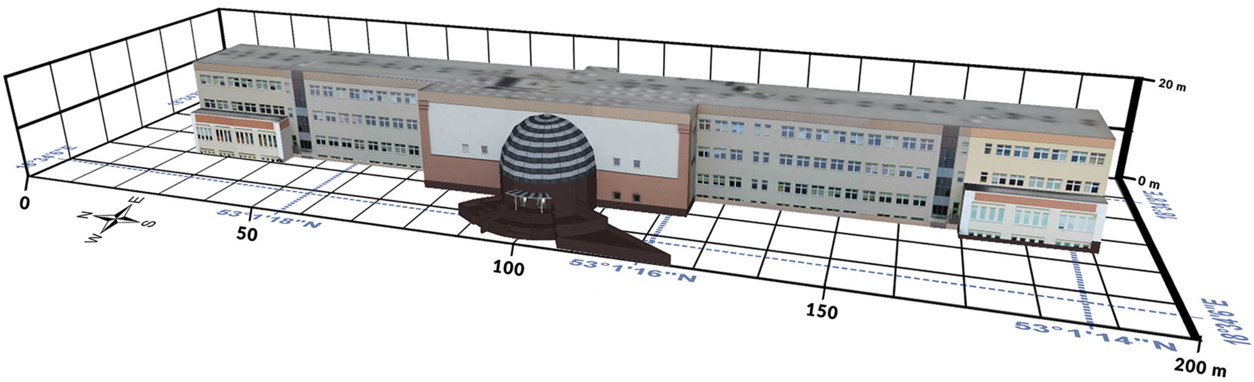

Fig. 1. Spatial model of the Faculty of Earth Sciences and Spatial Management at Nicolaus Copernicus University in Toruń prepared at the LoD3 level in Trimble SketchUp and ArcGIS Pro.

Fig. 3. Network Signal Info Pro application workspace with frequency and strength presentation of detected wireless networks in the Faculty of Earth Sciences and Spatial Management at Nicolaus Copernicus University in Toruń building.

eliminating measurement errors, and supplementing missing values through interpolation. Data with errors or missing values were supplemented using interpolation techniques, ensuring consistency and spatial continuity of the visualisation.

Interpolation process and statistical analysis

The interpolation of Wi-Fi signal strength in this study was performed using a combination of spline interpolation and inverse distance weighting (IDW) in 3D, resulting in a continuous representation of the signal distribution within the FESSM NCU. Spline interpolation was initially applied to generate smooth horizontal and vertical planes of signal strength. This method creates a continuous surface by minimising abrupt changes between data points, making it ideal for modelling gradually varying phenomena like Wi-Fi signals. The advantage of spline interpolation lies in its ability to accurately predict signal values in unmeasured areas while maintaining a realistic, smooth transition between known points (Smith, Jones 2004). To further refine the model, a regular grid of 3D points was established throughout the building. For each point, IDW 3D interpolation was applied to estimate the Wi-Fi signal strength. IDW is a widely used technique in which the influence of each measured point diminishes with distance, making it suitable for modelling spatial phenomena like signal strength, which weakens with distance from the source. This method provides a reliable estimation of signal values based on spatial proximity (Nowacki et al. 2022). The combination of spline and IDW 3D interpolation produced a detailed, continuous function that accurately represents the spatial variation of Wi-Fi signal strength in three dimensions. This approach not only captures the gradual changes in signal strength across horizontal planes but also provides insight into vertical variations, offering a comprehensive visualisation of the signal's behaviour throughout the building. This dual-method approach enhances the accuracy of indoor wireless network analysis by integrating both smooth surface modelling and point-based interpolation techniques. This technique enabled the reproduction of continuous changes in signal strength in 3D space, which is particularly important in visualising wireless networks. This technique is widely used in various fields of science and engineering, where precise spatial data analysis and visualisation are required (Smith et al. 2004). The interpolated data were statistically analysed in the ArcGIS environment (ESRI).

This analysis included calculating basic statistical measures, such as mean, median, and standard deviation, and identifying areas of low and high signal strength. In the latter element, voxelisation was applied as a 3D statistical analysis method, allowing for precise modelling and visualisation of signal strength distribution in space

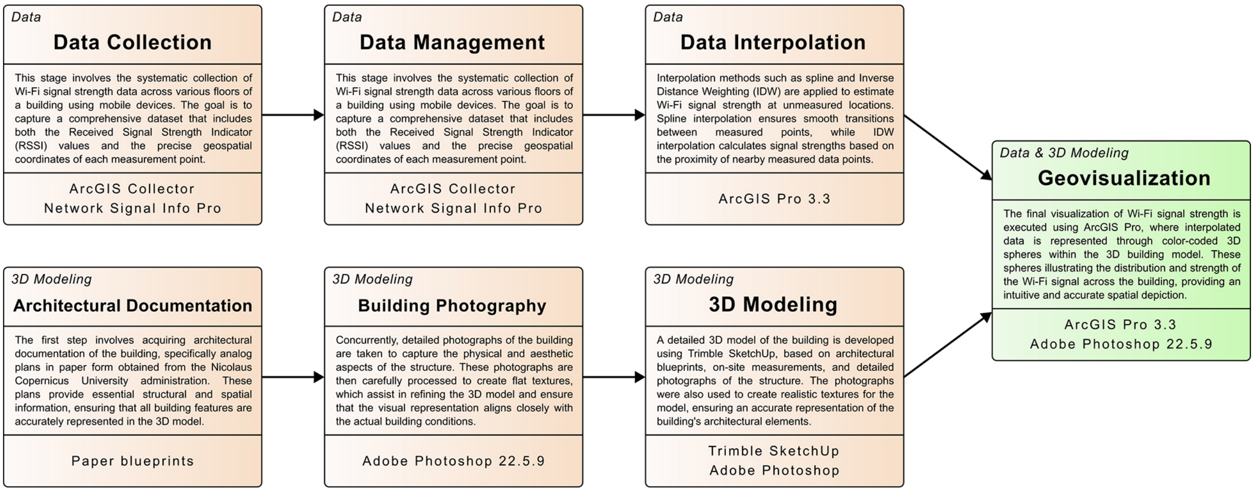

Fig. 4. The process of collecting and processing data to obtain the final geovisualisation.

(Fig. 4). Voxelisation involves dividing the space into regular 3D units called voxels, allowing for detailed analysis of signal changes in regular fields covering the entire object of interest (Li et al. 2015, Górniak, Kunz 2024).

The entire statistical analysis and data interpolation process was conducted according to known practices in GIS and spatial analysis, using data processing modelling, ensuring high quality and reliability of results. Thanks to advanced mathematical techniques and analytical tools, it was possible to obtain detailed and precise information about the spatial distribution of the Eduroam wireless network signal strength in the FESSM NCU building in Toruń.

Results

Analysis of Eduroam signal distribution in the FESSM NCU building

The primary focus of this study is to advance 3D GIS data visualisation methods. The core scientific contribution lies in the development of variable chromatic spheres – a novel technique for representing spatial variability in 3D environments. This approach offers an intuitive and accurate means of visualising signal strength across both horizontal and vertical dimensions, addressing the limitations of traditional 2D methods. Our proposed method contributes to overcoming these challenges by introducing new tools for detailed 3D geospatial analysis. The case study on Wi-Fi signal distribution serves as a demonstration of the broader potential of these techniques, which can be applied to other spatial phenomena. The conducted analyses revealed that the Eduroam wireless network signal distribution in the FESSM NCU building is highly varied, with areas of high, medium, low, and very low signal strength (Fig. 5). The 3D visualisation allowed for precise identification of these areas, which is crucial from both a user and technical perspective to improve signal quality and optimise network infrastructure.

Three-dimensional visualisations of the phenomenon

The obtained results showed that the strongest signal is available in the central parts of the building and near access points. On the other hand, areas such as basements and some rooms located at the edges of the building showed significant signal drops. This analysis allowed for the identification of so-called dead zones, places without wireless network access, and prompted the system administrator to take measures to improve this situation. Figure 5 presents the level of signal strength variation in the FESSM NCU building in Toruń. The Eduroam wireless network signal measurement was performed for three floors. On each floor, registrations were made at the following levels: at the base, in the middle, and under the ceiling, which at relative heights are, respectively, 0 m, 15 m, and 35 m. The phenomenon's distribution visualisation used the following colour scale: navy blue indicates very weak network strength (within

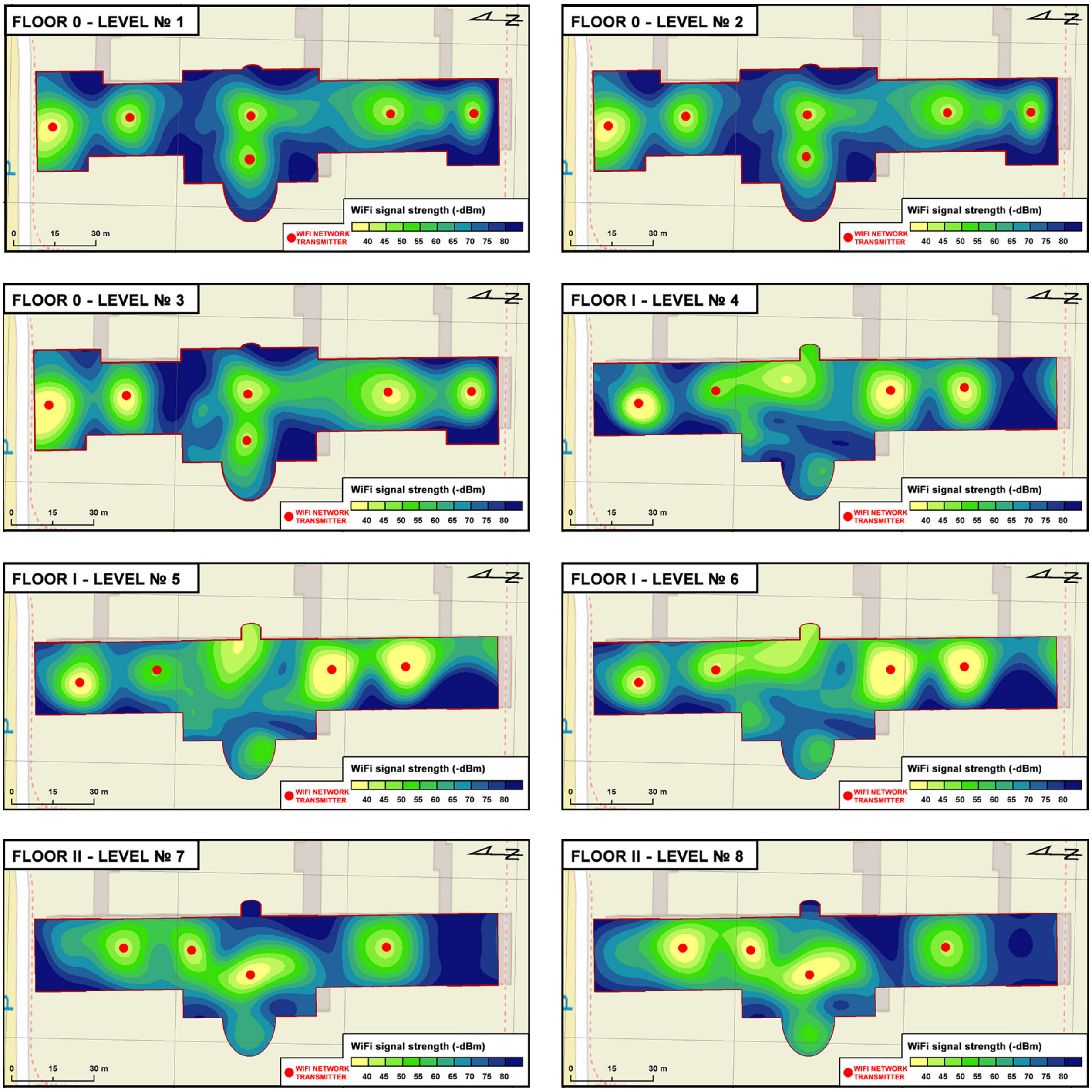

Fig. 5. Visualisation of Eduroam wireless network signal strength distribution on different measurement levels.

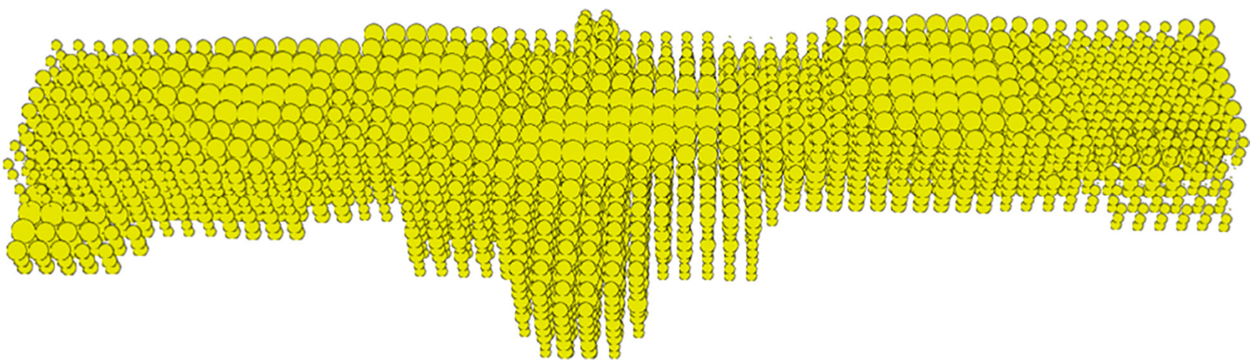

Fig. 6. Spatial distribution of Eduroam wireless network signal strength variation in the Faculty of Earth Sciences and Spatial Management at Nicolaus Copernicus University in Toruń building presented using the point method with symbol size as a graphical variable.

>80 dBm), while green-yellow colours indicate areas with the highest Eduroam network signal values (within 45 dBm). The locations of wireless network transmitters were marked with a red point symbol.

Figures 6 and 7 present 3D visualisations of the Eduroam wireless network signal strength distribution in the FESSM NCU building in Toruń. These examples illustrate actual differences in signal coverage and strength between different parts of the building, which is crucial for network users and system administrators for planning the placement of access points. For example, in lecture halls and laboratories where the number of users is the highest, greater signal strength variation was noticed. Three-dimensional models allow for accurate mapping of these differences, leading to better planning of network infrastructure to meet changing user needs.

Discussion

The primary scientific contribution of this study lies in the advancement of 3D GIS methodologies for wireless signal visualisation. By introducing variable chromatic spheres, we present a novel geovisualisation technique that enhances the accuracy and clarity of spatial data representation in complex indoor environments. This method provides a more intuitive understanding of signal distribution, enabling better identification of signal coverage areas compared to traditional 2D methods. The combination of spline interpolation and IDW 3D interpolation further solidifies the methodological contribution, demonstrating an effective approach to spatial interpolation in 3D spaces. This study contributes to the growing body of research on 3D GIS by offering a new method for visualising spatially dispersed phenomena, particularly in environments where

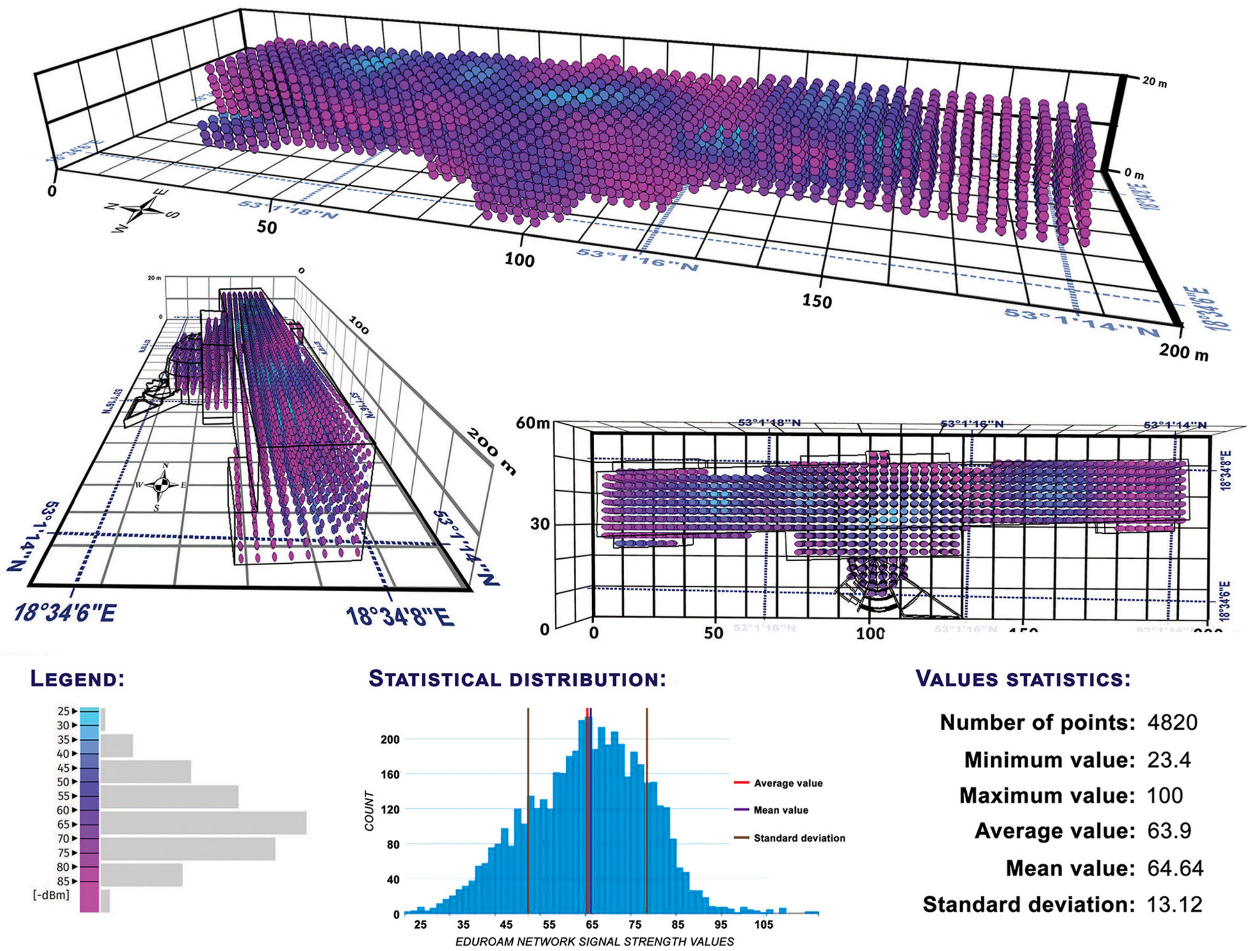

Fig. 7. Spatial distribution of Eduroam wireless network signal strength variation in the Faculty of Earth Sciences and Spatial Management at Nicolaus Copernicus University in Toruń building presented using the point method with colour intensity as a graphical variable along with selected statistical measures.

vertical signal variability plays a critical role (Biljecki et al. 2016, Nowacki et al. 2022). The Eduroam network is used as a case study, yet the significance of this research extends beyond the applied context. By expanding the possibilities for indoor geospatial visualisation, this study initiates a broader discussion within the academic community regarding the future of 3D GIS and its applications in wireless network analysis and beyond. Results obtained in the conducted study have wide practical applications, especially in academic, institutional, and user contexts. The 3D visualisation of the Eduroam wireless network signal, realised using the FESSM NCU building as an example, provides operational knowledge and practical information for both system administrators and end users of this network service. Thanks to the applied interpolation methods, the obtained models allow for the identification of weak signal areas and enable effective planning of access point placement and client zones.

Despite the strengths of the proposed methodology, several limitations must be acknowledged. The precision of the interpolation results is inherently dependent on the density and distribution of measurement points. In environments with insufficient measurement data, the accuracy of the spline interpolation and IDW 3D techniques may be reduced, potentially leading to less reliable visualisations. Furthermore, the current method assumes a homogeneous building structure, which may not account for materials or objects that cause signal attenuation. However, the adaptability of the methodology allows for its application in various other contexts. The approach can be extended to other wireless technologies, such as Bluetooth, LoRa, or cellular networks, and can be adapted for diverse spatial environments, including shopping malls, industrial complexes, and urban areas. By refining the model to incorporate material-specific attenuation and increasing measurement density, the visualisation technique can offer accurate insights across a range of use cases. Practical applications of the results also include the possibility of adapting the used methods to map parameters of other wireless technologies, such as Bluetooth, LoRa (Karpińska, Kunz 2021), or cellular networks. These methods are particularly valuable in areas where network availability is crucial for the functioning of information systems, such as hospitals, airports, or data centres, as well as in peripheral areas located outside urban zones.

Moreover, the development of 3D visualisation technology in GIS opens new possibilities for the education and training sector. Students can gain access to realistic 3D models that help them better understand the principles of radio wave propagation and the importance of device placement in the network. Such visualisations can also be used for demonstration purposes during research presentations at scientific conferences or technical workshops (Haeberling 2008).

The research not only serves as a practical case study but also contributes to scientific understanding by exploring advanced geovisualisation methods within 3D GIS environments. A key scientific aspect of this study is the introduction of variable chromatic spheres, a novel geovisualisation technique proposed by the authors. These spheres, colour-coded to represent different levels of Wi-Fi signal, provide a more intuitive and spatially accurate representation of signal distribution than traditional 2D methods. This visualisation method offers a new approach for indoor signal strength analysis and has not been previously documented in the literature. By enabling clearer identification of areas with weak or strong signal coverage, this innovation expands the possibilities for indoor geospatial visualisation, contributing to a more comprehensive understanding of wireless signal behaviour in complex indoor environments. While this case examines the Eduroam network within the FESSM NCU, the methodology can be applied to diverse wireless technologies and indoor environments. This study aims to initiate a broader discussion on 3D geospatial data visualisation in the context of wireless signal distribution, contributing to the scientific field by advancing the use of GIS for representing complex spatial phenomena. The development of this method fills a gap in the cartographic visualisation of indoor environments, which has not yet been widely presented in the literature.

Conclusions

This study is intended to stimulate discussion and future research on 3D geovisualisation methods, proposing that the techniques developed here have broader potential in fields ranging from digital cartography to spatial analysis of other dispersed environmental data. Pushing the boundaries of what is possible with 3D GIS, this research lays the groundwork for more advanced and comprehensive visualisation tools, which are critical for understanding complex spatial phenomena. The study on the 3D spatial visualisation of dispersed phenomena using the Eduroam wireless network signal strength analysis provided several important conclusions regarding both 3D GIS technology and the specificity of measurement data. Overall, this study lays the foundation for more comprehensive research into 3D GIS methods, encouraging future work in enhancing visualisation techniques and expanding their application to different spatial phenomena and environments. Based on the performed work, actions, and analyses, the following conclusions can be proposed:

Cartographic Principles in 3D Visualisation: The application of cartographic principles, which are traditionally employed in 2D maps, remains essential in 3D geovisualisations. These principles ensure the accuracy and clarity of spatial data representation, which is particularly important in complex environments like indoor spaces. The integration of GIS with advanced computer graphics is necessary to achieve precise and meaningful 3D visualisations. The development of robust tools that bridge the gap between GIS and computer graphics can enhance the overall accuracy and usability of 3D spatial models (Biljecki et al. 2016).

Limitations in 3D Interpolation: Current GIS software presents significant limitations in handling 3D interpolation for discontinuous and dispersed datasets, such as Wi-Fi signal strength. The lack of standardised solutions across different platforms restricts the detail and precision of the resulting models. There is a need for the continued development of 3D GIS methodologies that integrate theoretical principles of cartographic presentation and address interoperability issues among software providers (Nowacki et al. 2022). Standardising these methods will enhance the accuracy of spatial models and allow for more comprehensive 3D data visualisation.

Wi-Fi Signal Distribution in 3D Space: The distribution of Wi-Fi signal strength in 3D space is highly non-linear and varies according to several factors, with the building's structural elements and the positioning of access points being the most significant. Proper network design should consider an in-depth spatial analysis of the building's layout to optimise the placement of access points. This ensures effective signal propagation and minimises areas of weak coverage, contributing to more efficient network design (Rahman, Pilouk 2008).

Empirical Findings from the FESSM NCU Building: The empirical study conducted within the FESSM NCU demonstrates that the current layout of Eduroam network access points is optimal and does not require substantial modifications. However, a simulation that models the placement of additional access points may offer insights into potential improvements in network performance, especially in areas of high demand. Such simulations can be used to assess the impact of additional devices on signal strength distribution and overall network efficiency.

Challenges and prospects for further research

Despite significant progress in 3D data visualisation, several challenges require further in-depth research and development, as well as the realisation of additional case studies. One of the main shortcomings is the lack of standardisation in the tools and methods used for creating 3D geovisualisations. The diversity of software and the lack of uniform guidelines hinder the process of data integration and exchange between different GIS systems (Nourian et al. 2016). Another challenge is developing more advanced algorithms for full 3D data interpolation. Although the currently used methods, such as voxels, allow for a certain level of analysis, they often do not reflect the full variation of analysed phenomena in 3D space. Work on developing Voxel GIS solutions will be a significant step towards increasing the efficiency and applicability of the described technology (Zlatanova, Ghadikolaee 2015).

Further research should also focus on optimising field data collection and processing processes. The use of mobile GIS applications such as Collector for ArcGIS (ESRI), which enables offline work and real-time data updates, is essential for improving fieldwork efficiency (ESRI Inc 2015). In these considerations, one must not forget about education and the development of user competencies in geoinformation systems. Knowledge of modern tools and geovisualisation methods should be more widely available, allowing for better utilisation of this technology's potential in various fields of science and practice (Kolbe et al. 2024). Prospects for further research also include developing virtual reality (VR) technology and its integration with GIS systems. VR GIS can significantly expand spatial analysis possibilities, offering more intuitive and interactive ways of visualising and analysing data. Integrating VR technology with GIS can also open new possibilities in education, spatial planning, and crisis management.

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Author's contribution

G.G.: conceptualisation, data curation, formal analysis, methodology, investigation, project administration, resources, validation, analysis of results and formulation, preparation of figures, text correction, and writing – original draft. M.K.: supervision, conceptualisation, investigation, project administration, resources, validation, analysis of results and formulation of conclusions text correction, and writing – review and editing.

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