Journal of Electrical Engineering, Vol. 74, No. 5, 2023, pp. 422-433

sciendo

PAPERS

Methods of computer modeling of electromagnetic field propagation in urban scenarios for Internet of Things

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The paper investigates software solutions to simulate radio waves propagation in urban environment, specifically for the context of the Internet of Things (IoT). The purpose of the study is to provide a comprehensive guide for utilizing the Altair Feko software to obtain a detailed representation of the IoT network, its associated parameters and how they relate to the modeling of electromagnetic fields. It is beneficial to simulate the network during the design stage to obtain valuable data and make necessary adjustments. The key features of a Sigfox or other low power IoT network can be obtained by simulation, enabling an evaluation of the network design prior to its actual implementation. Given the growing demand for IoT devices and networks, researching the optimal design and performance of such networks is of great importance. This underscores the need for continuous exploration of effective methods to achieve efficient design and performance of IoT networks.

Keywords: internet of things, computer simulation, radio waves propagation, network, antenna design

1 Introduction

In the modern world, many problems that arise during the design stage of various systems can be solved with the help of computer simulation. In view of how effective the method is, there is a large number of simulation tools that consider various factors and allow for very accurate calculations of a system under consideration.

Computer modeling also finds its application in simulating the networks of the IoT. An IoT network consists of physical devices, sensors and machines that are connected to the internet or a local area network. These devices are capable of collecting, transmitting and exchanging data with each other. This network of interconnected devices provides real-time data analysis, automation and optimization. The importance of the IoT lies in its ability to provide new ways for physical system and environment optimization. By collecting and analyzing the data from sensors and devices, the IoT can provide valuable insights that can be used to increase efficiency, reduce costs and improve decision-making in various areas. The modern smart city implies the use of IoT, where interconnected devices and systems are used to optimize energy consumption, traffic flows and public safety, etc. It is worth noting that IoT also has scientific significance, which lies in its ability to develop various fields and industries, providing real-time data analysis, automation and optimization. Given the versatility and complexity of the system, for its well-coordinated work, it is necessary to design it with high quality. In this article, we will elucidate the simulation stages and evaluation of the IoT network from the point of view of radio communication between devices.

2 Subject and methods

Sigfox network is to be considered in our study. This technology is a member of the Low Power Wide Area Network (LPWAN) technology family, commonly employed in the development of IoT networks where low data volume, long range and minimal power consumption are crucial design considerations. It operates globally in multiple frequency bands, such as 868 MHz in Europe, 902 MHz in the United States and 915 MHz in Asia and Australia. These frequency bands are commonly designated for Industrial, Scientific and Medical (ISM) applications and operate without a license. Sigfox employs a star network topology in its communication infrastructure, whereby each end device communicates directly with the nearest base station. The base station then relays the data to the Sigfox cloud, where it undergoes processing and analysis by various applications. The network employs a range of techniques to ensure efficient communication in urban environment. One such technique is called Ultra Narrow Band

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https://doi.org/10.2478/jee-2023-0050, Print (till 2015) ISSN 1335-3632, On-line ISSN 1339-309X

modulation, where the signal is transmitted using a very narrow frequency band, which reduces interference and enables long-range communication with low power consumption [9]. Another used technique is called Time Division Multiple Access (TDMA), which is a method of sharing a single channel among multiple users by dividing it into time slots [5]. It is used to ensure the communication of multiple devices within a specified time frame. In the case of Sigfox, TDMA is used to allow multiple end devices to share the same frequency channel without interfering with one another. Each end device is assigned a specific time slot during which it is allowed to transmit its uplink message, ensuring that multiple devices do not transmit simultaneously and do not cause interference. Finally, Sigfox also uses a technique called Listen Before Talk (in some regions), which is used to ensure that an end device only transmits when the frequency channel is free. Before transmitting a message, the end device listens to the channel to detect any ongoing transmissions. If the channel is found to be busy, the end device will wait until it is clear before transmitting its message, thereby avoiding interference with other devices. Taken together, these techniques allow Sigfox to enable reliable communication between base station and end devices.

2.1 Calculation using FEKO tool

Altair Feko software is a popular tool for simulation of electromagnetic fields. It allows precise computation of various antenna parameters such as radiation pattern, input impedance and optimal placement relative to other objects. Special modules of the software also make it possible to simulate radio network coverage, frequency spectrum management, electromagnetic compatibility, radio frequency interference, etc. The above statements suggest that the simulation tool could be highly effective for IoT network design. The paper deals with the Sigfox IoT network: the simulation of the antenna patterns, electromagnetic field propagation and the signal-to-noise ratio both on the transmitter side and on the receiver side. An area of approximately 4 km^2 around the central railway station of Bratislava, Slovakia, has been selected for the simulation.

In the initial stage, it is necessary to create a model of the designated area that can be utilized within the Altair Feko software environment. The urban area is characterized by a high density of buildings and vegetation, which must be considered when modeling the network. The manual creation of buildings for a given area is not efficient in terms of time, given the large number of buildings that need to be created. This problem can be solved using the Blender program, which is designed to work with 3d objects. Thanks to its open-source code, the program can work with custom add-ons. The Blender GIS add-on [1] enables the acquisition of geographic information for a desired region by utilizing Google Maps as a source. This way we can obtain a basemap, elevations and presented buildings. The three-dimensional representation of the designated area is illustrated in Fig. 1 below. Afterwards we are able to export the resulting layout in Stereolithography (.stl) format, which can be imported into the Altair Feko environment.

The subsequent stage involves the modeling of the Sigfox base station antenna in Altair Feko. It may be beneficial to prepare a radiation pattern in advance. It eliminates the need to repeatedly simulate the antenna in the network on the city layout, thus reducing computational complexity. However, if there are multiple antennas in the network, each with distinct radiation patterns, the process of simulating each antenna and inserting its respective pattern into the layout remains necessary.

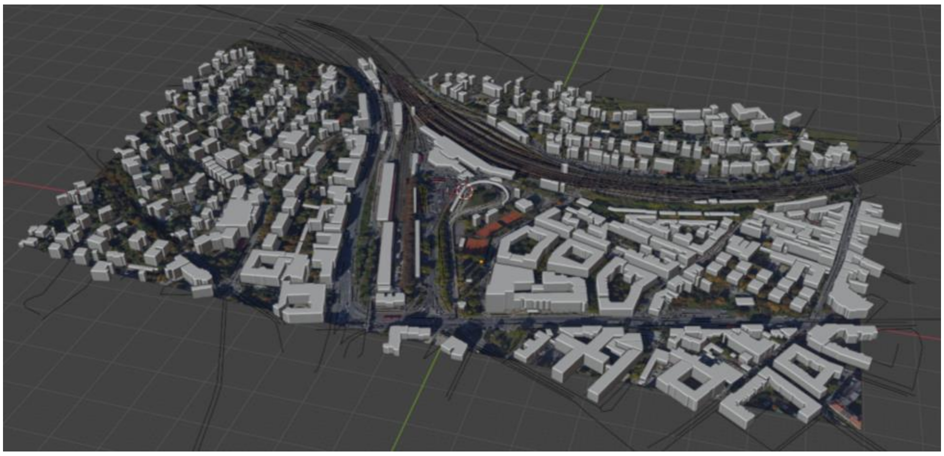


Fig. 1. The layout of the investigated area presented in Blender

To accomplish this task, we simulate an omnidirectional dipole antenna operating at a frequency of 868 MHz [9], as specified in the official Sigfox parameters. As a result of the simulation, we obtain the radiation pattern of the antenna, depicted in Fig. 2, and export it to ASCII file (.ffe) for further work with the project.

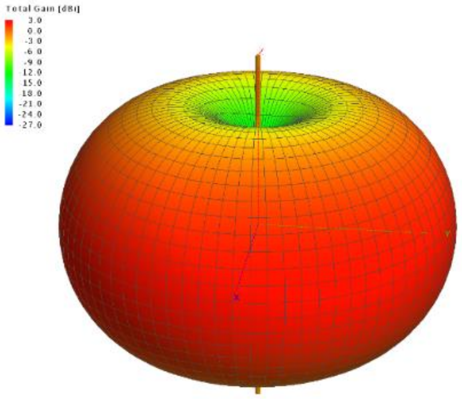


Fig. 2. Calculated dipole antenna pattern of a Sigfox base station

Having the city model as an .stl file, it can now be imported into Altair Feko for further analysis. Additionally, we can now import beforehand calculated radiation pattern of a base station antenna to the layout of the city and place it in the desired place. Upon identifying parameters of the calculation area, we can simulate the propagation of the electromagnetic field. Using described technique, the calculation takes approximately three hours. But it is also worth noting that the calculated area has been reduced in relation to the original layout. Figure 3 portrays the imported model, antenna pattern and simulation plane. In addition, it is important to consider that the accuracy of such calculations is limited due to the fact that the imported layout is identified as unknown mesh parts by Feko, which does not allow further modifications to it in the software, including the possibility to set the electromagnetic properties of materials. This problem can be solved by pre-processing the city model in Fusion 360. In this case, Altair Feko recognizes the file as a set of geometric elements, but in this scenario, the challenge arises from the extremely high volume of those elements. The program does not have the capacity to manage such a large number of objects. Considering the extensive time required for calculations, it would not be appropriate to further develop or improve the method discussed above. Based on our findings, the Altair Feko program can be used to obtain results on the propagation of electromagnetic fields in urban environments, albeit with limited accuracy and significant computing resources required.

2.2 Calculation using WinProp tool

The Altair software suite features a specialized tool for simulating radio wave propagation. The WinProp package, integrated with Feko, is dedicated to the calculation of electromagnetic field propagation in various environments, including urban and rural conditions.

The software enables manual creation of area layouts as well as utilization of diverse databases. To acquire the outcomes through this methodology, adherence to the outlined roadmap, as depicted in Fig. 4, is imperative. The area of interest has been exported from the OpenStreetMap website [2] as a vector data set in OSM format. The data contains an information about the buildings present in the area and their position in space, both vertically and horizontally, as well as a vegetation. However, it should be noted that the file does not contain topographic information. Relevant data can be obtained from the United States Geological Survey website [13]. The USGS provides free elevation data for any region on the globe. The website provides data of a minimum area of 1 by 1 degree. Therefore, the exported file must be preprocessed in the WallMan tool, which is also included in the Altair Feko package. Using the software means, it is necessary to select the desired area and ensure that the coordinate system of the topographic data matches the vector dataset with buildings and vegetation. After completing all the necessary settings, it is necessary to save the information as a Topography Database (.tdb) file. This file format enables us to combine the vector database with topographic data using the ProMan tool, which is bundled with the software package.

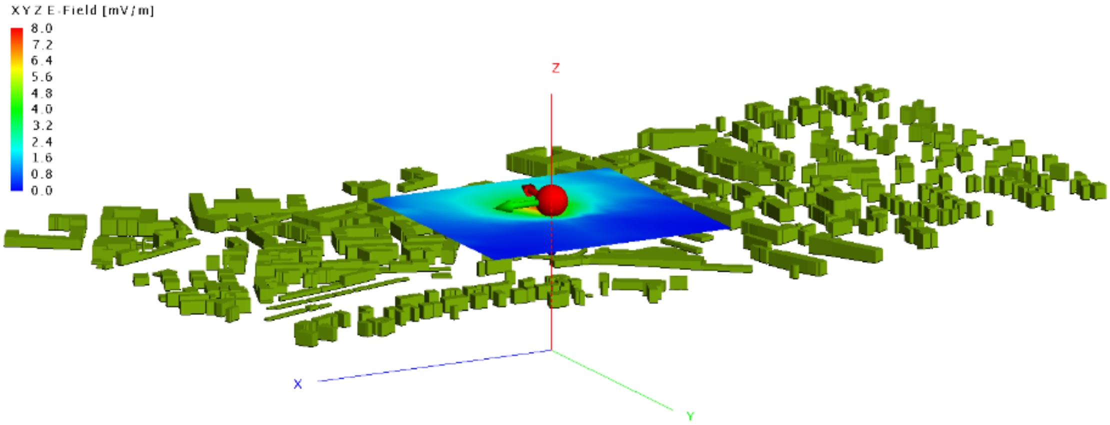


Fig. 3. Electromagnetic field propagation approximation in Altair Feko

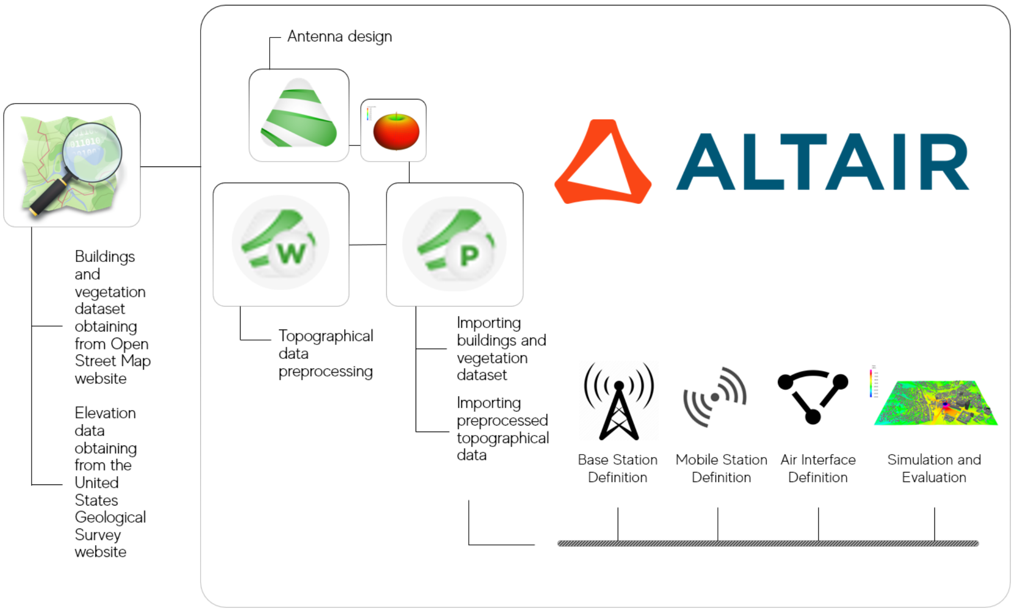


Fig. 4. Network simulation roadmap

In ProMan environment we place a base station antenna of the Sigfox network, set its radiation power and add its pattern to the calculated earlier in Feko. It is also possible to set the parameters of the receiver antenna in the corresponding menu. Thus, we import monopole antenna pattern, calculated in Feko, beforehand to represent the receiver antenna in the studied model.

Upon completion of necessary preparations, the system is now prepared for simulation. Due to the specific focus on calculating the propagation of radio signals, the simulation takes very little time. With a resolution of 10 meters and only one antenna, the task has been accomplished in seconds. Which is an excellent result, especially in comparison with the 3 hours that the Feko base program took to calculate even a several times smaller area. Naturally, as the accuracy of calculations and the number of antennas present increase, the simulation time is expected to increase exponentially. But even in this case, the program remains extremely efficient in terms of time. For example, with calculation resolution of 1 meter and the presence of 40 antennas in the study area, the calculation takes about 20 minutes. As a result of the simulation, we get a graphical display of the signal strength of the base station within the study area, which is shown in Fig. 6. At this point we are able to evaluate how the urban landscape affects the propagation of the radio signal.

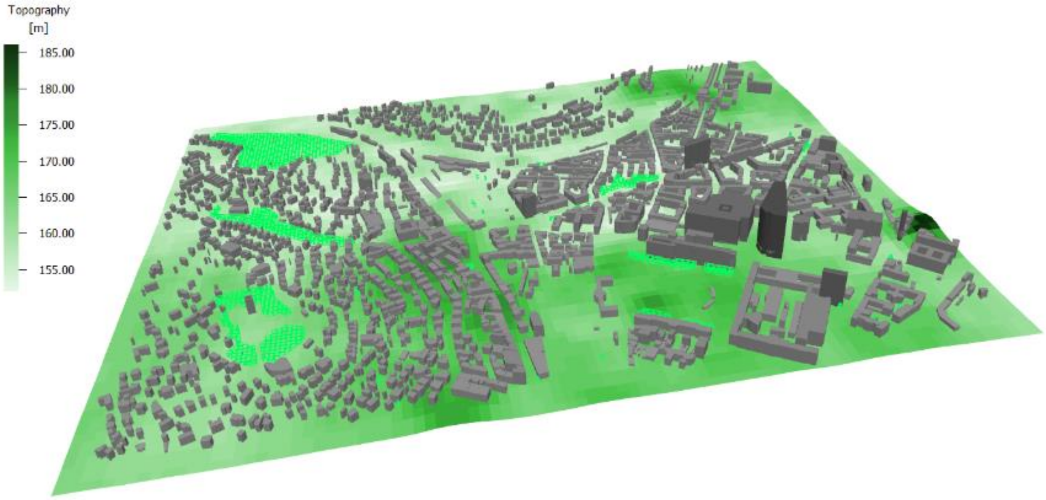


Fig. 5. Completed database that includes buildings, vegetation, and topographic data of the region of interest

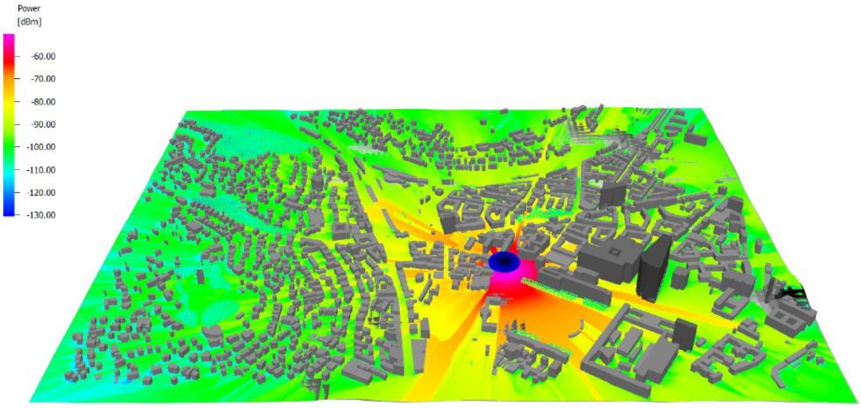


Fig. 6. Calculated radiated power of the base station considering the receiver antenna

Altair ProMan also allows to simulate an entire network. To accomplish this, it is necessary to configure the air interface. However, one may take into consideration that Sigfox downlink communication is different from traditional downlink multiple access schemes used in wireless communication systems. When downlink communication is required, Sigfox uses a unique scheme called Ultra Narrow Band to send small amounts of data to devices [5]. This approach is different from traditional schemes, where the base station sends data to multiple devices simultaneously using time division or frequency division multiplexing. Instead, Sigfox UNB scheme uses a unidirectional communication link from the base station to the device, allowing the base station to conserve power and resources. The ProMan tool does not consider this non-typical communication approach, thus limiting its capability to simulate only uplink communication with maximum accuracy. Nevertheless, setting the appropriate network parameters allows for obtaining extensive data that characterizes the network being studied. This being said, we can acquire an information regarding the signal-to-noise-plus-interference ratio (SNIR) in terms of uplink communication. It is possible to determine whether Sigfox end device, located in a specific place, can successfully transmit data to the base station. Furthermore, it is now possible to investigate the minimum required transmitting power of an end device to attain the desired SNIR level. In the context of co-site interference mitigation and battery life extension, having this knowledge allows for setting the power level at the lowest possible value. Figure 7 illustrates the calculated SNIR and the minimum required Tx power for uplink communication, presented from left to right, respectively.

It is worth noting that Sigfox protocol utilizes a variety of techniques to mitigate interference when two end devices in close proximity send a message at the same time. It uses Ultra Narrow Band modulation and Time Division Multiple Access. This implies that the SNIR level obtained through simulation will be minimally impacted by the presence of multiple end devices located in close proximity, as well as any ambient noise present in an urban environment.

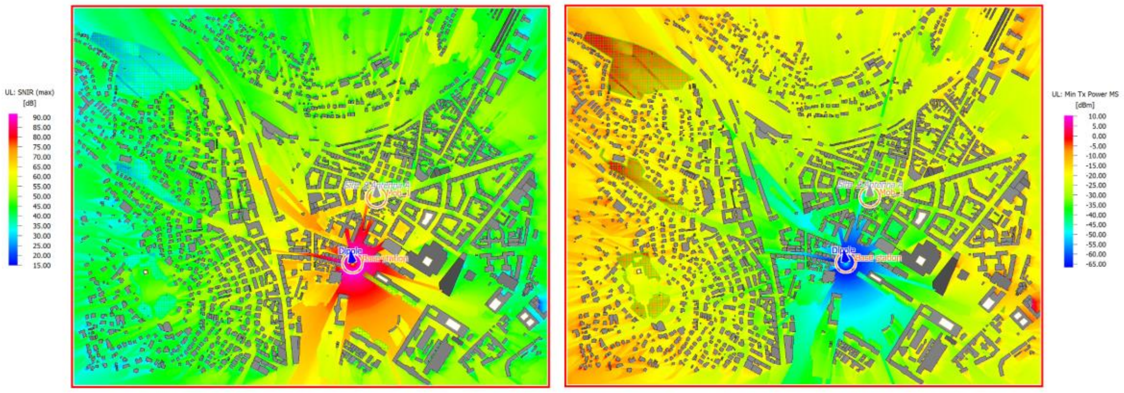


Fig. 7. Calculated level of SNIR and minimum Tx power of end devices

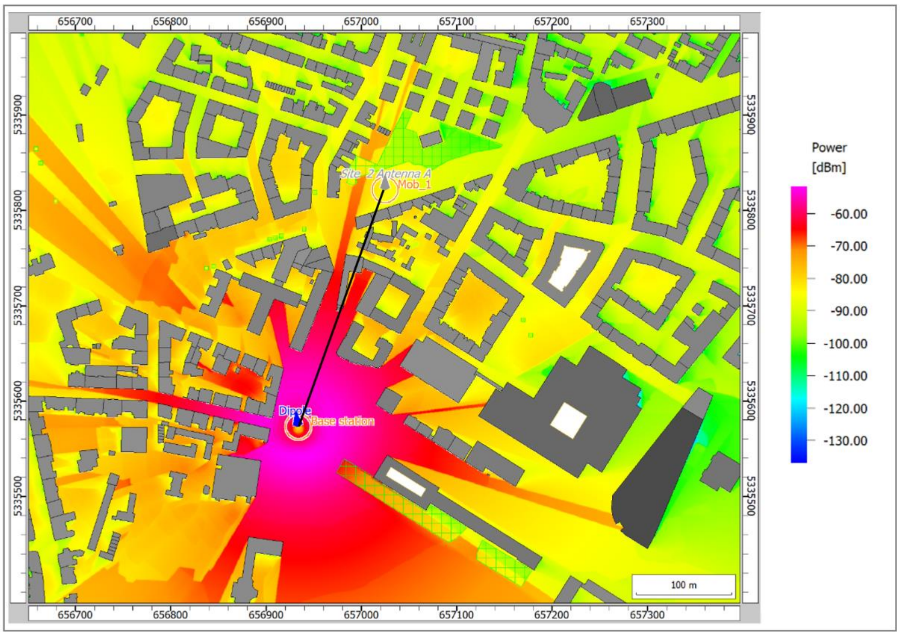


Fig. 8. Calculated radiated power of the base station

2.3 Comprehensive analysis of outcomes

In this section of the article, the simulation results are closely examined, with specific focus on the radiated power of the base station. The reduced area of interest is considered, as depicted in Fig. 8. It is evident that in the immediate proximity of the transmitter, along the line of sight, signal strength values range from –60 to –80 dB. As we move farther away from the base station antenna, the signal weakens. Beyond the line of sight, the received signal values range from –75 to –95 dB and likewise attenuate with increasing distance from the signal source. Figure 9 illustrates a graph depicting the signal strength along the path from the base station antenna to the antenna of the mobile end device as represented by the black line in Fig. 8.

Furthermore, an assessment of Signal-to-Noise-plus-Interference Ratio (SNIR) values along this designated path provides valuable insights into the overall communication performance. This metric, which accounts for both the signal strength and interference levels, is crucial in determining the quality of reception at the mobile end device. By evaluating SNIR along this specific trajectory, we can gain a comprehensive understanding of the communication link robustness and potential areas for enhancement. Let us conduct a more in-depth analysis of the SNIR levels within the region of interest and examine its corresponding graphical representation: Fig. 10 and the corresponding graph depicted in Fig. 11, which illustrates the SNIR levels along the propagation path from the base station to the mobile antenna.

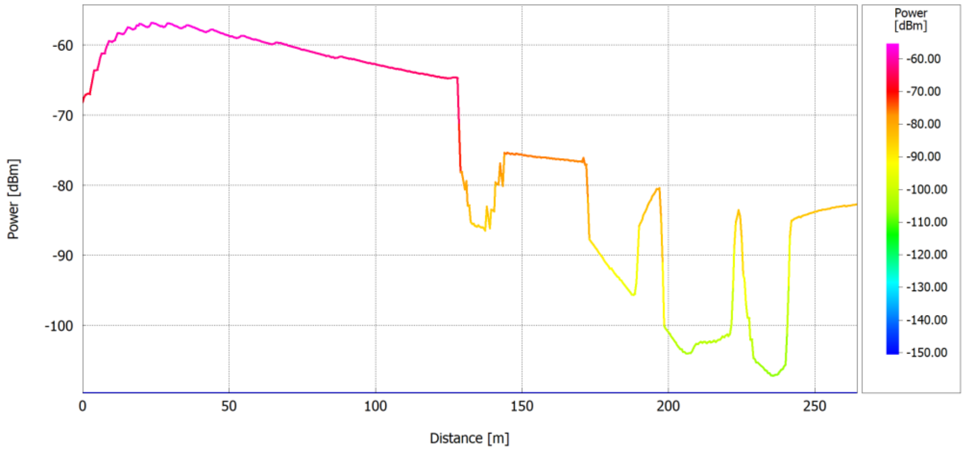


Fig. 9. Calculated signal strength along the given path

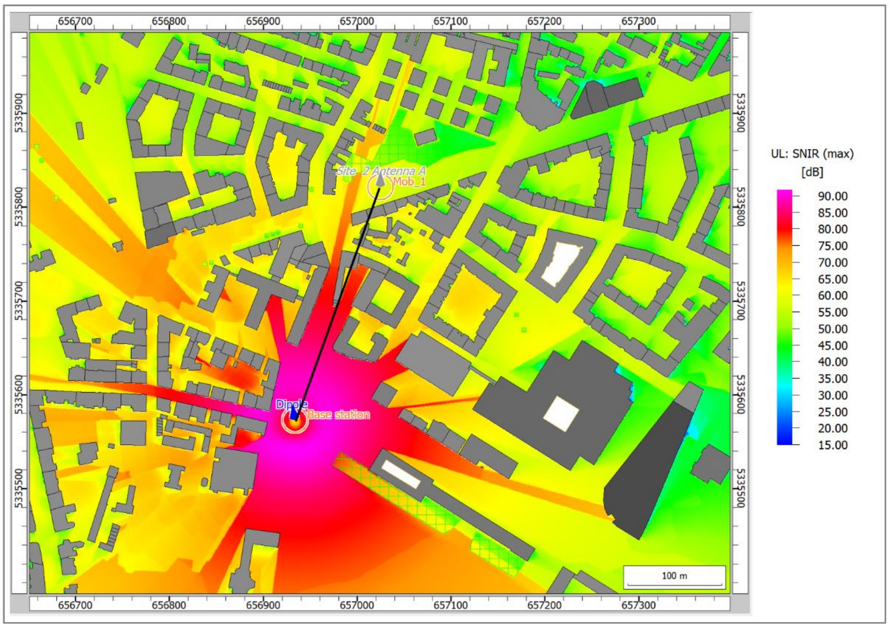


Fig. 10. The calculated level of SNIR in a zoomed-in view

It is important to highlight that when factoring in the receiver antenna operation within the network, our results pertain exclusively to the outdoor environment. Consequently, signal levels within buildings are not represented in the graph below; gaps in the data correspond to areas obstructed by structures along the signal path which is represented in Fig. 10.

Moreover, examining the minimum required transmit power for end devices is essential for optimizing the network overall performance. This parameter plays a pivotal role in ensuring reliable and robust communication links between the base station and mobile end devices. By comprehensively assessing the minimum required transmit power along the designated path, we can make informed decisions regarding resource allocation and network configuration to achieve the desired level of service quality. Figure 12 displays the graphical representation of the simulation pertaining to the minimum required transmit power of end devices. The graph in Fig. 13 delineates the corresponding values along the propagation path (indicated by the black line) from the base station to the end device.

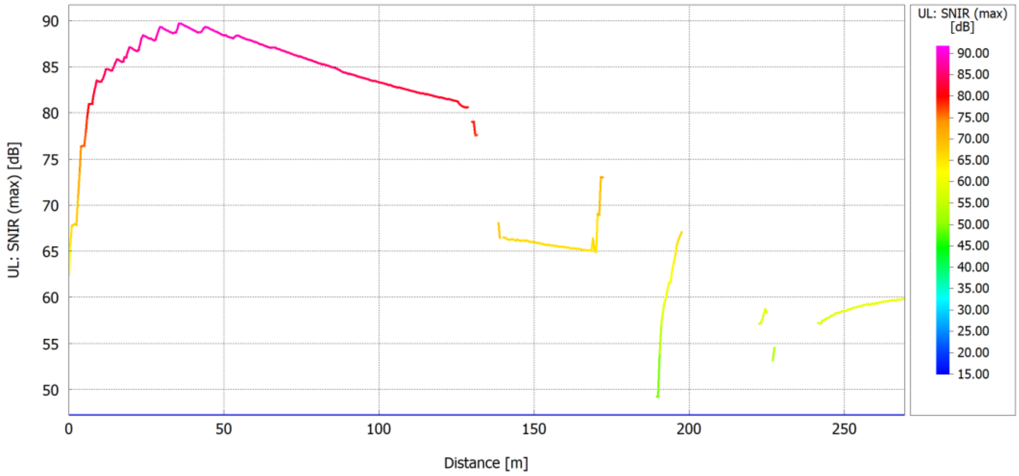


Fig. 11. Calculated SNIR level along the given path

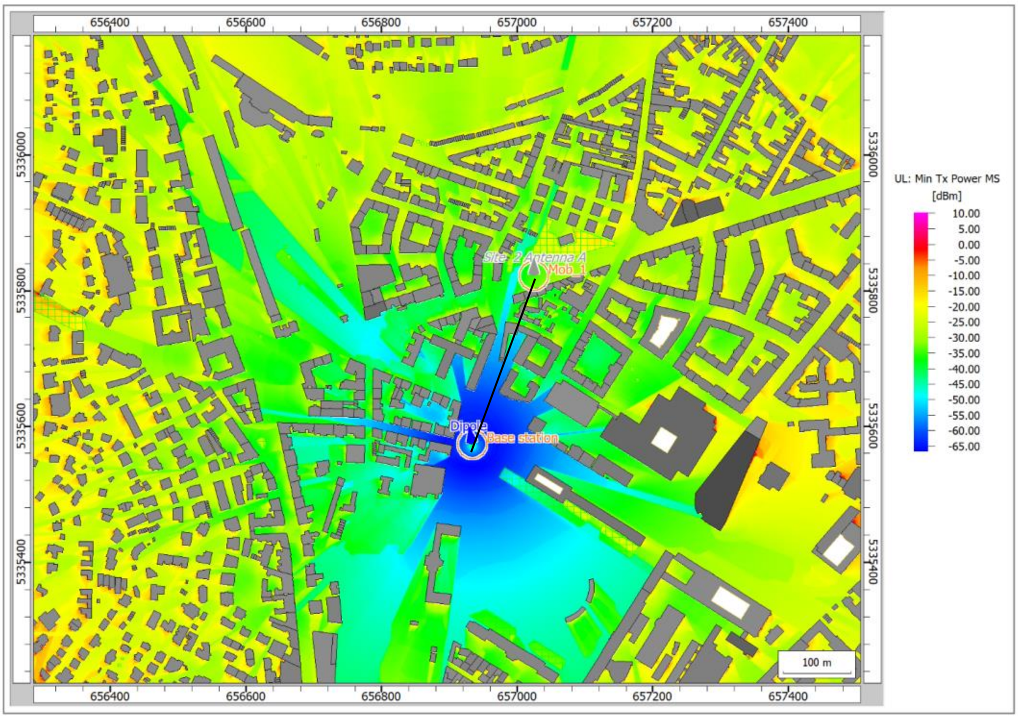


Fig. 12. Calculated minimal required Tx power of end devices in terms of uplink communication

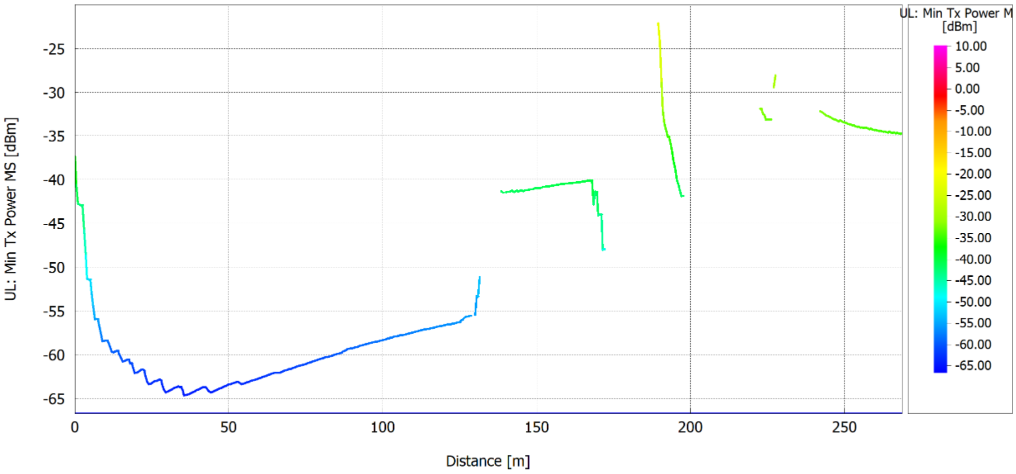


Fig. 13. Graph of calculated minimal required Tx power of end devices

2.4 Comparison of simulation results with analytical model

To ensure a rigorous evaluation of model simulations, it is imperative that we juxtapose the obtained results with those derived from analytical models. Losses attributed to terrain, foliage and buildings can arise from various phenomena, including diffraction, reflection, absorption, or scattering. These models elucidate methodologies for determining the median (50%) path loss as a function of distance and prevailing conditions. Each of these models draws on empirical data, at times supplemented with theoretical extensions, to provide a statistically representative or median estimate of anticipated path loss [4].

Among the reference models, the Okumura-Hata model stands out as one of the most widely employed. It encompasses graphical data gleaned from the Okumura model [3, 6, 12]. Notably, the model offers three distinct formulas tailored for urban, suburban and open areas. In our context, we will specifically consider the formulation applicable to urban conditions:

$$L_{50}\ (\mathrm{dB}) = 69.55 + 26.16 \log f_c - 13.82 \log h_t - a(h_r) + (44.9 - 6.55 \log h_t) \log d$$

where

$150 < f_c < 1500,\quad f_c$ in MHz,
$30 < h_t < 200,\quad h_t$ in m,
$1 < d < 20,\quad d$ in km,
and $a(h_r)$ is the mobile antenna height correction factor.

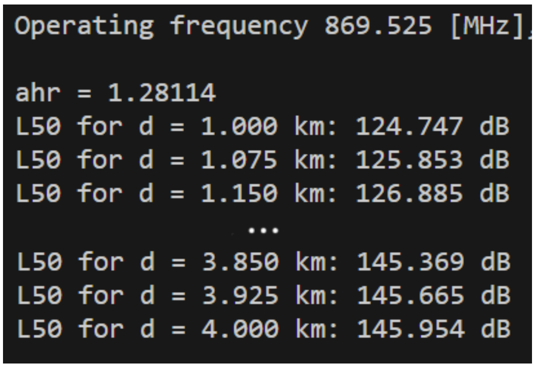
For a small- or medium-sized city

$$a(h_r) = (1.1 \log f_c - 0.7) h_r - (1.56 \log f_c - 0.8) \qquad 1\ \mathrm{m} \le h_r \le 10\ \mathrm{m}$$

and for a large city

$$a(h_r) = \begin{cases} 8.29(\log(1.54 \cdot h_r))^2 - 1.1 & 150\ \mathrm{MHz} \le f_c \le 200\ \mathrm{MHz} \\ 3.2(\log(11.75 \cdot h_r))^2 - 4.97 & 200\ \mathrm{MHz} \le f_c \le 1500\ \mathrm{MHz} \end{cases}$$

It is important to emphasize that for accurate results, it is necessary to consider distances beyond 1 km, and the emitter antenna should be positioned at a minimum height of 30 m. Therefore, our input parameters for the calculations are as follows: operating frequency of 869.525 MHz, transmitter height of 30 m, receiver height of 2 m and a medium-sized city. With these specified parameters, we will compute the median path loss within a range of 1 to 4 km, with increments of 75 m. To streamline this process and avoid iterative calculations, we will develop a program to utilize the Okumura-Hata model formula to perform these computations. This approach not only saves considerable time but also affords us the flexibility to adjust distance and step size as needed without further manual recalculations. The output of the program is shown in Fig. 14.



```
Operating frequency 869.525 [MHz]

ahr = 1.28114
L50 for d = 1.000 km: 124.747 dB
L50 for d = 1.075 km: 125.853 dB
L50 for d = 1.150 km: 126.885 dB
                ...
L50 for d = 3.850 km: 145.369 dB
L50 for d = 3.925 km: 145.665 dB
L50 for d = 4.000 km: 145.954 dB
```

Fig. 14. The output of the program to calculate the median path loss by Okumura-Hata model (transmitter height 30 m, receiver height 2 m)

In the subsequent phase, we are to execute a simulation using the Altair ProMan software, employing analogous input parameters: operating frequency of 869.525 MHz, transmitter height set at 30 m and receiver height at 2 m. The resultant simulation output, the median path loss, is depicted in Fig. 15.

The graph, presented in Fig. 16, illustrates the median path loss along the trajectory displayed in Fig. 15 by a black line. It provides a comprehensive visual representation of the signal attenuation characteristics in this specific scenario.

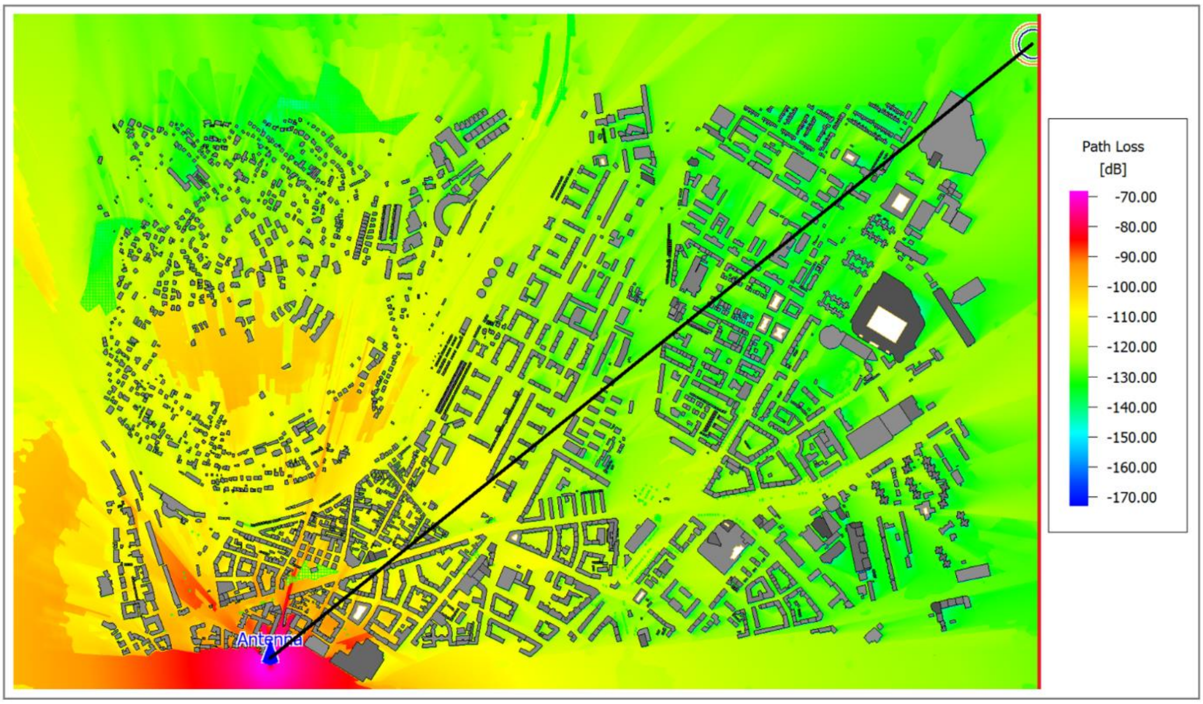
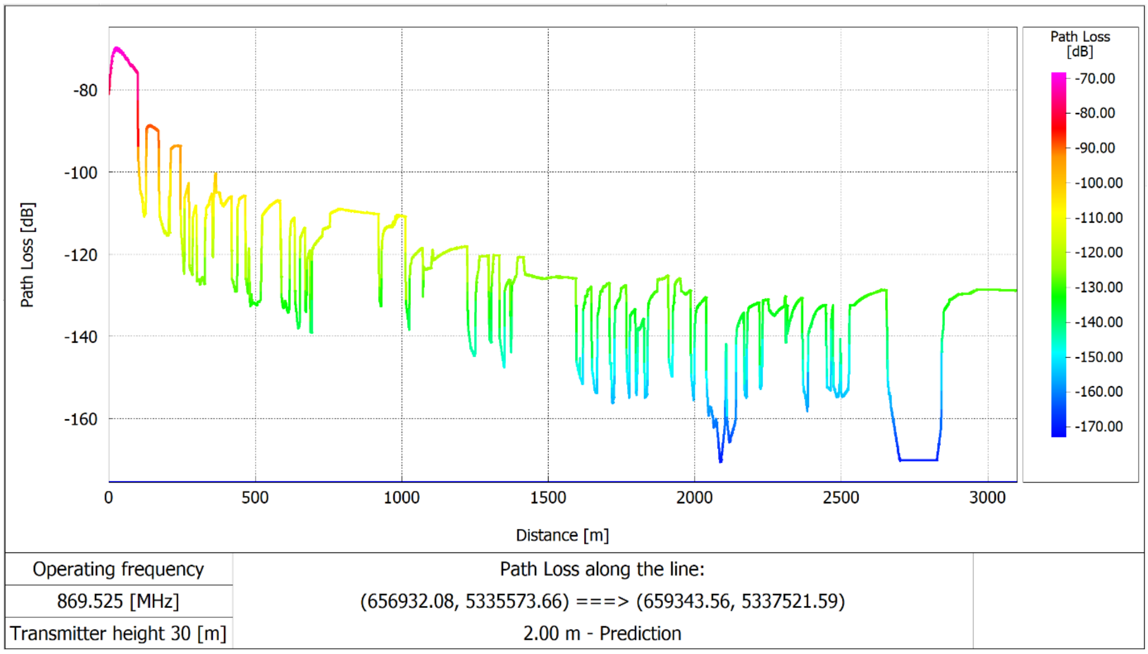


Fig. 15. Calculated median path loss in the region of interest



Operating frequency
869.525 [MHz]
Transmitter height 30 [m]

Path Loss along the line:
(656932.08, 5335573.66) ===> (659343.56, 5337521.59)
2.00 m - Prediction

Fig. 16. Graph of the calculated median path loss along the given path

The graph above vividly illustrates an exponential decrease in the signal level. The pronounced troughs correspond to significant signal level drops, indicating obstruction by buildings along the path. To enable a comprehensive comparison between the outcomes of the Okumura-Hata model and the ProMan simulation, data outputs from both scenarios were extracted and subsequently employed to construct graphical representations via Microsoft Excel, as illustrated in Fig. 17 below.

It should be kept in mind that the Okumura-Hata model provides accurate results starting from a distance of 1 km. Consequently, values preceding this range are not depicted on the graph. Additionally, our ProMan model has a confined simulation area, with the maximum distance from the transmitter to the model edge being approximately 3 km. It is noteworthy that within the range of 1 to 3 km, we observe generally comparable outcomes from these two distinct approaches in obtaining the median path loss.

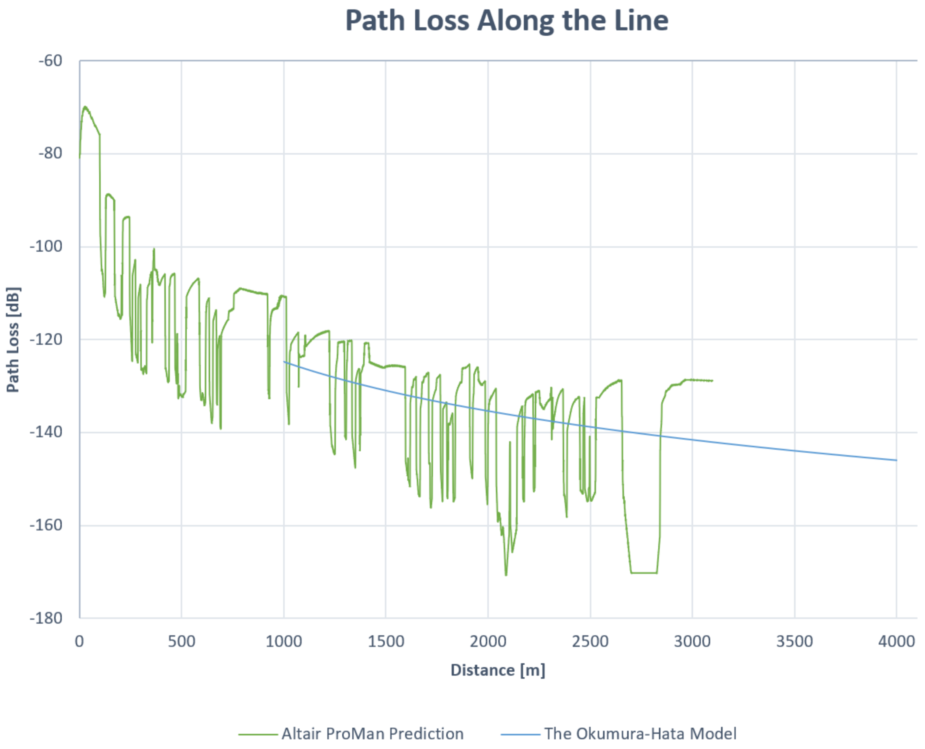


Fig. 17. Comparison of calculated median path loss: Altair ProMan *versus* Okamura-Hata Model

It should be kept in mind that the Okumura-Hata model provides accurate results starting from a distance of 1 km. Consequently, values preceding this range are not depicted on the graph. Additionally, our ProMan model has a confined simulation area, with the maximum distance from the transmitter to the model edge being approximately 3 km. It is noteworthy that within the range of 1 to 3 km, we observe generally comparable outcomes from these two distinct approaches in obtaining the median path loss.

3 Results and conclusion

Our study reveals that the Altair Feko and WinProp software package provides highly effective means of simulating electromagnetic field propagation. It is possible to model the complex urban landscape, which incorporates various features such as buildings, vegetation and topographic information. Provided software facilitates all stages of modeling, from the preparation of the region of interest and antenna design to the precise configuration of the entire network and communication protocols employed. The resulting calculations enabled us to obtain a comprehensive map of the radio signal propagation for each individual antenna relatively to the base station and the entire radio network coverage, including the signal-to-noise ratio and interference. Furthermore, an examination of the Okumura-Hata model was conducted and the results obtained from its calculations were compared with the Altair ProMan simulation outcomes. This allowed for a comparative analysis of approximations of the same phenomenon, albeit obtained through entirely different methods. Upon comparing the obtained graphs, it can be argued that both models enable the acquisition of a reasonably accurate understanding of the median path loss along a given trajectory. It is noteworthy that the software can provide additional data beyond the scope of our study.

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Received 19 July 2023