Minimizing the number of signal sources in 802.11 wireless networks

Arkadiusz Dobrzycki, Krzysztof Skórcz, Andrzej Tomczewski
Poznań University of Technology
60-965 Poznań, ul. Piotrowo 3a, e-mail: {Arkadiusz.Dobrzycki, Andrzej.Tomczewski}@put.poznan.pl

The paper presents a computer program algorithm developed in order to minimize the number of signal sources (access points) in wireless networks of the 802.11 standard with the use of the Monte Carlo method. It includes an objective function of economic character and a set of technical limitations. The paper covers also the basics of determining the signal level within the 802.11 network range with the use of the directives provided in recommendation ITU-R P.1238-6. The algorithm developed was implemented in a .NET environment (C# language). Sample calculations were performed, the results were discussed and the directions for further development related to the present subject matter were indicated.

1. Introduction

The demand for temporarily and spatially unlimited access to data is very high in an information society. This results in a constant search for new teleinformation technologies and in the development of the existing ones, especially in the area of wireless technologies. One of the technologies that is used but also intensively developed is wireless networks operating in the 802.11 standard. Its evolution has led to an increase of the bit rate in the 802.11n in relation to the original 802.11 specification, for which the parameter amounted to 1 Mb/s, by a few hundred times. Many technologies, including digital modulation with

Orthogonal Frequency-Division Multiplexing as well as simultaneous use of many input and output antennas (MIMO - Multiple Input Multiple Output) that makes it possible to include the multipath phenomenon in electromagnetic wave propagation, contributed to that effect. The physical properties of the materials that the propagating signal encounters cause considerable losses and lead to transmission range limitations. In the case of open space, the decrease in signal level is so insignificant that, according to the 802.11n standard for antennas for wireless network interface controllers, the range achieved is 250 meters. The mathematical model that is considered in this case makes it possible to quickly evaluate the signal level and the potential conditions required for correct data transfer.

The interiors of buildings where construction elements (walls, ceilings, construction barriers) lead to particularly strong damping of electromagnetic radiation and reduction of the network range [4, 7, 8] represent a different situation. Additionally, the walls and ceilings of complex architectural objects, e.g. department stores, office buildings, etc. are often constructed in varying thickness and made of materials of varying damping properties. This leads to the necessity to appropriately place the signal sources which will make it possible to access the network with the set bit rate in the whole building and often with the additional condition of radical signal level reduction outside of the object's cubature. Fulfilling the requirements mentioned with the assumption that the investment completed in that area should be as low as possible requires the use of an optimization algorithm. In the cases where economic factors (usually the costs) are included in the optimization process, an efficient approach is defining an objective function in the form of an economic criterion (e.g. the price of the solution). The technical aspects of the problem can then be considered in the form of a set of functional constraints of the optimization process conducted.

Different solution methods – deterministic or stochastic – can be used depending on the form and on the complexity of the optimization task defined. For many technical system optimization tasks that are defined nowadays, the deterministic methods pose too many limitations. This refers in particular to the cases where the objective functions are multimodal with a large number of decision variables and where they are of heterogeneous nature. Such constraints are not present in the case of stochastic methods, starting from the classic Monte Carlo method and ending with evolution algorithms. In the present work, a modification of the Monte Carlo algorithm utilizing the capabilities of multi-core processors designed for PC computers and workstations was used to solve the optimization task formulated.

2. 802.11 wireless network standard

2.1. General characteristics of the 802.11 standard

The documents describing the hardware and software parameters of wireless computer networks are collected in the 802.11 standard set. They include, among others, the values of transmission parameters that must be met by the equipment used. Such a solution makes it possible to quickly evaluate the technological advancement of the equipment. Differences between the standards are connected with the network frequency (2,4 or 5 GHz), maximum power of radiated signal (10 or 20 dBm) as well as the maximum speed and the theoretical network range. Table 1 presents a summary of radio network standard parameters. The summary does not include the 802.11ac standard as there are few devices of that type available now and the standard itself is still in the development phase. The forecast date when the work on the standard should be completed is the end of 2013 or the beginning of 2014. Now (the status as of September 2012) the work on the first version is 91% complete [5]. What is particularly interesting are the assumed parameters regarding the planned and the maximal bit rate which should amount to 1,3 Gbps [6].

Table1. Basic parameters of radio networks in the 802.11 standard

Standard	**802.11**	**802.11a**	**802.11b**	**802.11g**	**802.11n**
Range inside / outside [m]	20/100	35/120	38/140	38/140	70/250
Maximum transfer speed [Mbit/s]	2	54	11	54	600
Frequency [GHz]	2,4	5	2,4	2,4	2,4/5
Maximum transmitter power [mW]	1000	1000	100	100	100/1000
Modulation type	FHSS, DSSS, IR	OFDM	HR-DSSS, CCK	HR-DSSS, CCK, OFDM	OFDM

Regardless of the wireless network operation standard used, its bit rate depends on signal strength where the key parameter is the power of the transmitter and the strength of the input signal for a particular receiver. The producers of those devices provide, usually in table form, the dependency between the bit rate and the input signal level for receivers of specific types and models [7].

2.2. Signal level determination method for building interiors

In accordance with the guidelines for designing wireless networks for building interiors presented in recommendation ITU-R P.1238-6, the propagation model should be used. It can include three basic ways of electromagnetic wave propagation that directly influence the network range [4, 7, 8]:

- the only damping factor in the network range planned is the air (there are no obstacles with higher damping properties),
- the signal encounters obstacles whose damping properties are many times higher in comparison to the air, such as: walls, barriers, pillars, etc. (no ceilings),
- the network planned will include a few storeys and the signal will have to travel through the ceilings.

In accordance with the basic propagation model recommended by the ITU organization (International Telecommunication Union) [8], establishing signal losses inside the building at the distance d from the transmitter should be performed considering a simplified version of the last two of the cases described above. Thus, the dependency according to which the total signal loss is then calculated takes the following form:

$$L_{total} = 20 \cdot \lg(f) + N \cdot \lg(d) + L_f(n) - 28 \quad [dB] \tag{1}$$

where: f – signal frequency [MHz], N – distant damping ratio, d – distance between the transmitter and the receiver (greater than 1 m) [m], L_f – ratio dependent on the number of ceilings through which the signal travels.

The values of the N and L_f ratios are determined empirically and they are provided in the tables (the values assumed depend on the type of material from which buildings of particular assignment are typically constructed and on the signal frequency). The recommendation distinguishes the following assignments: residential, office, commercial.

The model expressed through the dependency (1) is of empirical nature and includes internal building elements (walls, poles, ceilings, etc.) that damp the electromagnetic wave with the frequency values used in the 802.11 standard only in an averaged way.

Using the model provided, a computer program [3] determining the signal level at the receiver input in relation to the distance from the signal source – access point (AP) was developed. Figures 1 and 2 show the results of calculations respectively for the storey where the AP is located and between storeys. It was assumed that the antenna is placed 1 m above the floor surface level and the signal level for the storey examined is determined at this height. In turn, the calculations between storeys are performed along the axis that is orthogonal to the floor surface and that goes through the AP. Additionally, it was assumed that the AP emits the signal with the maximum power allowed according to the 802.11n standard – that is 10 dBm.

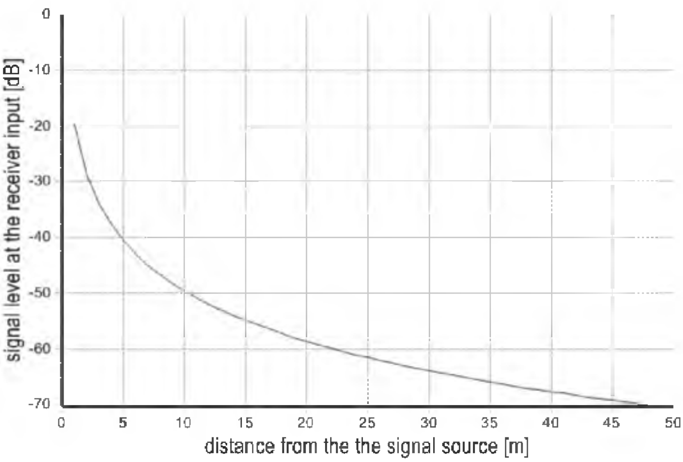

Fig. 1. Signal level at the receiver input in proportion to the distance from AP for one storey

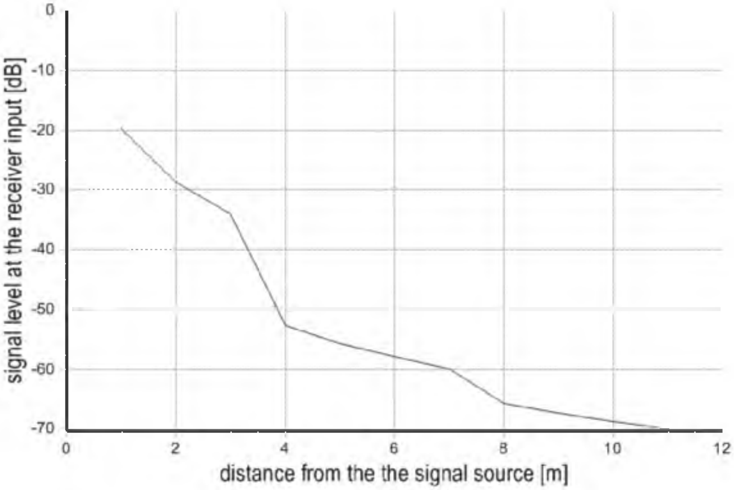

Fig. 2. Signal level at the receiver input in proportion to the distance from AP between storeys

The analysis provided above shows that the decisive factor influencing the signal level, and thus – the transfer speed in the wireless network, is the fact that the signal needs to travel through the ceiling. However, such an approach is not free from faults. The main problem that must be considered is, for example, the number of walls and the material from which they are constructed – for the basic model those values are averaged for a given building type (assignment). The interiors where wireless networks are used in practice are very often complex building objects with multiple barriers constructed of different materials and of different thickness. This results in varying radio signal damping ratios in different object areas. In relation to the above, the recommendation used provides also the dependencies that make it possible to determine the signal loss when passing through vertical obstacles (walls) more precisely than in the case of dependency (1). In this case, the conductivity σ and the electric permittivity ε_1 as well as the distance covered by the wave are considered. The recommendation under consideration provides a description of an approximate way of determining the material parameters mentioned above depending on the frequency of the signal transmitted. In accordance with the guidelines, the signal loss is determined as the sum of partial losses on all the obstacles as well as in open space. Assuming that the signal passes through M walls described by means of the appropriate material dependencies, and through n ceilings and including the wave propagation in open space, the total signal losses at the distance from the transmitter to the calculation point can be described by means of the following dependency [8]:

$$L'_{total} = 20 \cdot \lg(f) + \sum_{k=1}^{M} 1636 \cdot \left(\frac{\sigma^{(k)}(f)}{\varepsilon_1^{(k)}(f)} \right) \cdot d^{(k)} + L_f(n) - 28 \quad [dB] \tag{2}$$

where: k – wall index, $d^{(k)}$ – distance covered by the wave travelling through the wall with the index k, $\sigma^{(k)}$ – the conductivity of the material of which the wall with the index k is constructed, $\varepsilon_i^{(k)}$ –the electric permittivity of the material of which the wall with the index k is constructed.

3. Optimization of the number and location of access points in complex building objects

3.1 Problem characteristics, the selection and the model of the optimization method

The optimization process involves searching for a solution that satisfies the extreme condition of the quality evaluation criterion assumed $J(\mathbf{x})$ referred to as the objective function, where **x** is the decision variable vector. In the case of electric system optimization, varying criteria including technical factors directly related with the problem analyzed or economic factors (often the costs) indirectly related to the system (e.g. cost of materials, cost of production, project costs) can be used. The majority of problems related to technical systems are solved with the use of optimization algorithms with limitations. This results from the lack of technical capability to implement certain solutions which is connected with the technologies, materials, and machines used in the production process that are available now. The constraints are divided into structural ones – related to vector **x** elements, and functional ones – including all other conditions that the implemented system must satisfy.

Appropriate use of optimization methods in solving technical problems makes it possible to achieve considerable improvement of usage parameters of the systems analyzed, lower the costs of their production and exploitation, prolong their service life, etc. in comparison to non-optimal systems even if they are technically correct (compliant with standard requirements, recommendations, etc.). Using deterministic methods for that purpose makes it possible to achieve high solution accuracy and repeatability but this is valid only for problems that are described in analytical terms, defined in a single modal research space and that include a limited number of decision variables. Such limited application conditions mean that it is stochastic algorithms (Monte Carlo, hill climbing, simulated annealing, evolution, and others) which make it possible to solve global optimization problems with variables of different types (integer, Boolean, real) and with their number counted in hundreds that are used more and more often. In most cases, the faults of the group of methods mentioned above in the form of decreased quality of the solutions in relation to the precise value and problems related with their repeatability do not pose an obstacle in using them for engineering purposes. The increasing number of practical implementations of stochastic methods is also connected with the achievement of high computational power of the processors designed for PC computers (multi-core processors) and with the efficiency of the group of algorithms mentioned above in optimization of particularly complex technical systems.

The paper presents an attempt to solve the problem of optimizing the number and the location of access points to a wireless network of the 802.11 standard inside a physically complex building object whose construction parameters: geometry, internal divisions, material types, etc. are known. The basic goal of solving a task defined in such a way is finding the geometry of the arrangement of signal transmitters in the network of the 802.11 standard which will make it possible to achieve the minimal assumed signal level in the whole area of the building. Thus, the solution of the problem makes it possible to maintain the set data transfer speed at any point in the building.

Due to the multi-modal nature of the objective function, it was assumed that one of the stochastic methods will be used to solve the problem. In the case of small differences between local extreme values, using deterministic methods does not guarantee a correct solution. This is connected with the fact that the algorithm gets blocked in the local extreme attraction areas.

Considering a moderate number of decision variables and the ease of implementation with the use of contemporary programming system on the .NET platform, the Monte Carlo method will be used to solve the problem. Belonging to the group of statistical methods, the method makes it possible to obtain a solution of approximate nature. Assuming that the solution to the problem analyzed is designated with S (a single number, a set of values), determining the result with the use of the MC method is described by means of the following dependency:

$$\hat{S} = f(\{r_1, r_2, \ldots r_n\}, \ldots) \tag{3}$$

where : r_1, r_2,...r_n – is a set of random numbers (pseudo-random in calculation practice) used in the process implemented.

Because of the stochastic nature of the operations performed, the positive value is substituted with an expected value $E(S)$, which is represented by the integral I with the following form:

$$I = \int_0^1 \ldots \int_0^1 f(x_1, x_2, \ldots x_n) \mathrm{d}x_1 \ldots \mathrm{d}x_n \tag{4}$$

When defined in such a way, the method makes it possible to use the general algorithm in different calculation areas, the most important of which, apart from the independent optimization algorithm, are: solving linear equation systems, differential equation systems, integral equation systems, integrating functions with multiple variables, game theory simulations and serving as a component of other stochastic optimization methods, the so-called heuristics and meta-heuristics.

Due to an important fault of the classic Monte Carlo method connected with the fact that a very large number of draws must be performed, its sequential variation was used in the optimization of the problem characterized above. It is a random version of the deterministic method of successive approximation to determine the extreme. The method is iterative and based on the change of the value of the subarea that is analyzed in a given iteration and located around the best solution obtained from the previous iteration. The scale of the subarea is usually determined in a deterministic way so that the series of subsequent solutions would be characterized at least with no decrease of the value of the evaluation criterion, and ideally – with an increase of that value [2].

Additionally, a modification of the sequential Monte Carlo method was used for the purpose of increasing the efficiency of the algorithm for solving the problem presented in the present work. The modifications introduced are as follows: dependency between the number of draws and the size and level of complexity of the geometric and physical structure of the analyzed object and decreasing the number of draws per iteration number to the set low-bottom limit of the following value - n_{IMIN}. The method suggested makes it possible to analyze a multi-modal solution space which means that it prevents the algorithm from getting blocked in the local extreme attraction areas. The condition required to satisfy the assumption mentioned above is performing a large enough number of draws. In order to reduce the global analysis time without losing a satisfactory level of precision, parallelization of the algorithm with the use of multi-core processors designed for PC computers and work stations was introduced.

3.2 Decision variables, objective function, constraints

The algorithm developed assumes that the maximum number of access points located in the analyzed space at one time is $n_{APMAX}>0$. It was also determined that the decision variable vector **x** includes: the type of the access point used, the number of access points $n_{AP} \leq n_{APMAX}$ and their location coordinates (x, y, z). The length of vector **x** is thus a function of the number of signal sources located in the building and it can vary from 5 to $5 \cdot n_{AP}$. The economic parameter in the form of the total cost of investment related to the purchase and installation of the access points was assumed as the solution quality criterion. The form of the objective function used in the calculation algorithm is described with the following dependency:

$$J(x) = n_{AP}(c_{AP} + c_I) + c_D + c_P \qquad (5)$$

where: $J(\mathbf{x})$ – objective function, n_{AP} – number of access points, c_{AP} – unit cost of the access device, c_I – unit cost of network device installation (established as a percentage of the access device price), c_P – project cost, c_D – cost of labor and additional elements required to install and commission the network, e.g. configuration and activation.

Two constraints of technical nature including: controlling the signal level in the building and signal uniformity defined as the relation of the minimal value to the average value have been assumed with respect to the problem defined above. It should be noted that the parameters mentioned directly affect the second component of the process implemented – the location of access points. The analyses do not include the signal level outside of the building analyzed. This aspect of the problem will be discussed in subsequent works.

The constraints described above were considered with respect to the $J(\mathbf{x})$ function with the use of the penalty function. This leads to a modified formulation of the objective function $J_z(\mathbf{x})$, which includes penalty functions in a standardized form:

$$J(x) = f(n_{AP}, c_{AP}, \ldots, F_f) = n_{AP}[(c)]_{AP} + c_I) + c_D + c_P + \sum_{j=0}^{n_0} w_j F_{kj} \quad (6)$$

where: F_{kj} – standardized penalty function for j – this limitation, n_o – number of constraints used, w_j - weight (constant) j – of the penalty function.
The penalties used are of static character and they do not depend on any parameter of the iteration process performed.

In accordance with the description provided above, the Monte Carlo method, due to its stochastic character, is suitable for solving multi-modal problems. What should, however, be considered in the implementation of the algorithm is that increasing the precision of the end result means increasing the number of draws and often also modifying the calculation procedures used to determine the value of the objective function. The actions mentioned result in considerable extension of the global task completion time and disqualify the method from use in the case of problems with a very large number of decision variables.

3.3 Computer program implementation of the optimization system

On the basis of the optimization algorithm presented above and the propagation model expressed by means of dependency (2), an application designed to:

- enter the geometry of a multi-storey building object,
- determine the location and the material of internal construction barriers (walls, poles, etc.),
- place the access points to a 802.11 network,
- determine the signal level (decrease) distribution at the set height for particular storeys of the object,
- optimize (through a sequential Monte Carlo algorithm) the number and the distribution model of access points,
- visualize the results – signal level (decrease) distribution at the set height for particular storeys of the object,

was developed. The implementation was performed in the C# language with the use of the technological capabilities available on the .NET platform, in particular – through the use of object-oriented programming techniques and the resources of the .NET Framework library. A set of specialized classes was designed and the controls, structures, classes, interfaces, enumerated types and mechanisms designed for the purpose of parallelizing the performance of particular processes (`Thread` and `BackgroundWorker` classes) [1] were used for the development of the application structure. The last of the programming elements mentioned above were used to start the calculation of signal level distribution in a secondary thread as well as for synchronizing information about their progress with the use of controls from the main application form (handling through the main thread). Object of the generic `Dictionary` list class that make it possible to store `<Model,Calculator>` object pairs, where `Model` represents the model of the building and `Calculator` contains most of the calculation mechanisms [1], were used for the purpose of storing the data and the results. The optimization algorithm implemented uses random elements. The implementation of this type of elements in computer systems most often includes the so-called pseudo-random number generators [1]. In the case of the programming environment used for the implementation of the generator, the `Random` class including all its available methods is used.

Figure 3 presents a block diagram of the application developed, including the division of the $J_z(\mathbf{x})$ objective function calculations into the available number n_W of threads in the multi-core processor used.

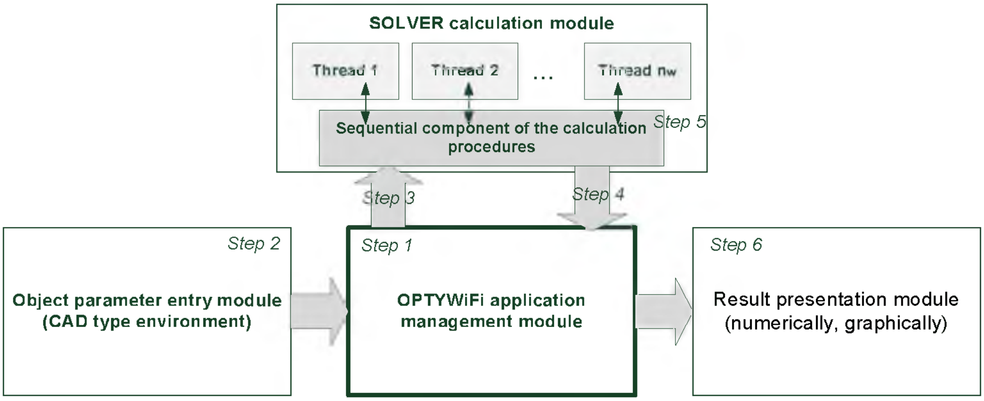

Fig. 3. The block structure of the application designed to optimize the number and the location of access points inside building objects with parallelized calculation module

4. Calculation example

The process of optimizing the number and location of access points inside a complex one-storey office building with the following dimensions: 19 x 19 m and the height of 2.4 m was performed with the use of the application developed. It was assumed that the calculation grid nodes are located 1 meter apart towards the x, y, and z components. The walls of the building as well as other barriers were constructed of bricks with the total thickness of 0.4 m. The technical data of the access points whose parameters were entered into the database designed to be used by the application were used in the calculations. The calculations are performed assuming the external isotropic characteristics of the antennas used. The condition of maintaining correct data transfer at the speed of 6 Mbps was accepted which means that the signal loss level for the access point types that can potentially be used cannot exceed D_{dB} = 88 dB. In addition, it was assumed that the minimum uniformity value of signal loss level distribution for the analyzed height must not be lower than 0.7. Figure 4 presents a screenshot of the application developed with the geometry configuration of the object analyzed.

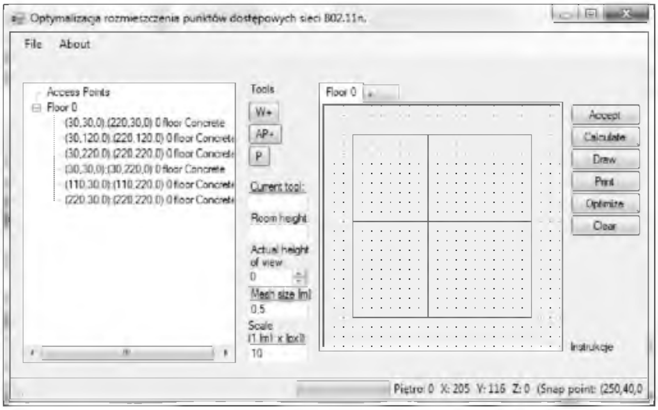

Fig. 4. The geometry of the analyzed object with internal walls indicated. Optimization of the distribution of access points in the 802.11n network

In accordance with the concept of the algorithm, the values of decision variables are drawn considering their location within the set of acceptable values (acceptable area) X. In the example implemented, the location of the access point is described by means of the numbers of calculation grid nodes which is equivalent to the absolute values of location coordinates. This also means that there is a finite number of combinations of coordinates for the x, y and z components specifying the location of the access point.

In accordance with the model provided in the form of dependency (2), an analysis of signal level distribution in specific points is performed for every draw. The calculations are performed in the central point of the elementary cube created by the grid nodes set for the x, y and z with the distance between the nodes for the analyzed case set to 1 m. The set value of grid spacing guarantees technically adequate level of precision, and using fast multi-core processors reduces calculation time to the level acceptable for the user and amounting up to 15 minutes depending on the geometry of the object and the number of access points placed in the object. In the course of the analysis performed, it was assumed that the access points distributed in the building have identical technical parameters in all the draws performed. Thus, stochastic changes in the transmitter power are not included. Additionally, it was assumed in the analysis that there is no interference from neighboring networks of the radio type that could cause real decrease in the transfer speed. During the analysis, the best (the highest) signal level, that is – the level resulting from the influence of one access point, was determined for every calculation point. The MIMO (multi input multi output) technology is not included in the model used.

Completing the optimization process in accordance with the algorithm described above resulted in obtaining the configuration of five access points of the TL-WA701ND type (output power - 17 dBm, maximum transfer speed - 150 Mbps). Assuming that the signal sources are placed in accordance with figure 5 in every node of the discretization grid used, the condition set with respect to the acceptable signal loss level is met. With no interference from external networks, the data transfer level of 6 Mb/s is guaranteed at any point inside the object. At the same time, the solution selected guarantees the lowest cost of the investment related to the design and implementation of a WiFi network with the parameters provided above and the best level of signal uniformity inside the whole building. The following values of the parameters required have been assumed for the purpose of determining the value of the objective function: c_{AP}=109 PLN, c_I=50%c_{AP}= 54.5 PLN, c_P= 300 PLN and c_D= 0 PLN.

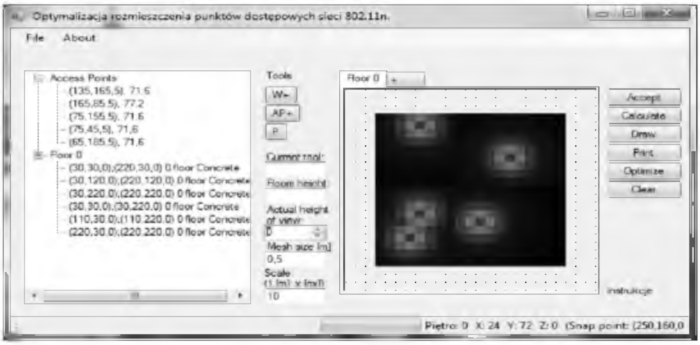

Fig. 5. The results of optimizing the number and the distribution of access points in the analyzed object. Optimization of the distribution of access points in the 802.11n network

An important parameter with respect to controlling the solution achieved is the distribution of signal loss level at the set height in the analyzed object. Figures 6a and 6b provide graphical presentation (2D and 3D respectively) of the distribution of signal loss level inside the building at the set height of 1.5 m. Its value does not exceed the set value of D_{dB} = 88 dB in any of the points. This means that the optimized system satisfies one of the constraints set. The value of the signal level uniformity measured at the height of 1.5 m from the floor surface is 0.703, which is also higher than the assumed value.

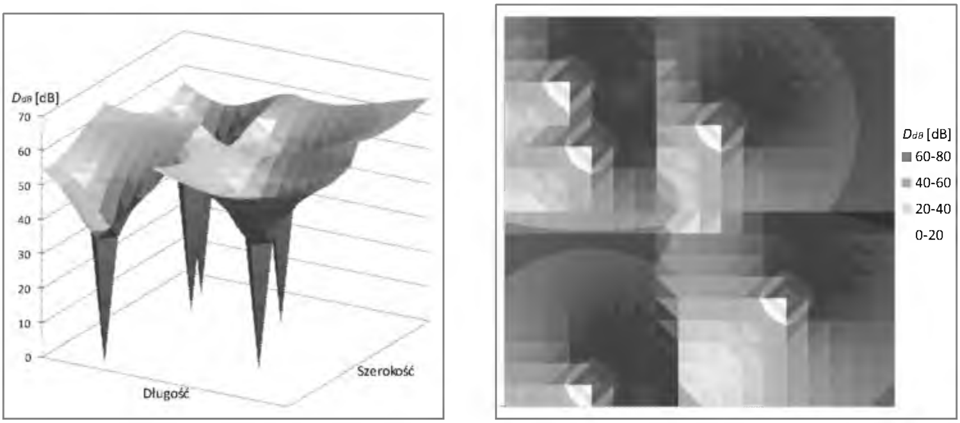

Fig. 6. Distribution of signal loss level D_{dB} in the analyzed room at the height of 1.5 m above the floor level: a) 3D b) 2D

5. Conclusions

Due to the dynamically growing number of places where the wireless technology WiFi is used as a method of providing the users with stable network access, optimization of the number and the method of distribution of network signal sources in building objects pose a vital problem. Nowadays, designing this type of systems requires including objects of heterogeneous geometric and material structure. Using the most basic form of the propagation model provided in recommendation ITU-R P.1238-6 for objects with the characteristics mentioned above does not guarantee the results that would be precise enough. The calculations performed should, thus, include the physical parameters (e.g. the thickness and the material) of the building construction elements which considerably influence the real range of the radio network.

Using an objective function of economic character makes it possible to include the aspect of investment and exploitation cost into the optimization of technical systems which pose a decisive argument for or against the adoption of a given solution for many investors. Such an action does not change the characteristics of the task as satisfying all of the additional technical parameters set in the standards, recommendations, and assumption is included in the form of a group of problem limitations, usually of functional character.

In the case of the objective function of multi-modal character, using deterministic optimization methods is effective only to a limited extent and often impossible. The stochastic elements used in the optimization algorithms make it possible to omit the areas to which local extrema are attracted and achieve a global solution to the problem. It must, however, be noted that the solution is of approximate character and that there might be differences in subsequent solutions obtained.

The algorithm developed and its computer implementation made it possible to obtain the assumed signal level and signal uniformity values with the minimal number of access points placed in the building. Their distribution with respect to one another results from the geometry as well as the thickness and the material of internal construction elements at which step changes of the signal level occur. Sample optimization calculations for a building of a defined structure of internal barriers led to the determination of the number and distribution of five access points for which the value of the established form of the objective function (6) is minimal and equals 1117.50 PLN. While analyzing other aspects of the calculations performed, the fact that the cost of network equipment purchase has been lowered in relation to non-optimal solutions that satisfy all the conditions set should be noted. The basic reason why such an effect can be achieved is using an objective function of economic character.

Further works on the subject presented should regard:

- extending the signal level calculation algorithm so that it would include stochastic changes of the transmitter power in time,
- including the influence of additional (interfering) radio signals, e.g. from other networks of the radio type operating in the vicinity,
- improving the quality of the results of the optimization process through changing it to one of the efficient evolution methods, e.g. the genetic algorithm method.

References

[1] Dobrzycki A., The range of wireless networks in buildings, Poznan University of Technology, Academic Journals, Electrical Engineering, No 67-68, 2011, pp. 49 - 54.

[2] Dobrzycki A., Zasięg sieci bezprzewodowej w obiektach budowlanych, Proceedings of XVI Scientific Conference Computer Applications in Electrical Engineering, Poznań, kwiecień 2011, ss. 299-300.

[3] Dobrzycki A., Skórcz K., Tomczewski A., Zastosowanie metody Monte Carlo do minimalizacji ilości źródeł sygnału w budynkowych sieciach 802.1. Zeszyty Naukowe Politechniki Poznańskiej Poznan University of Technology, Academic Journals, Electrical Engineering, No 69, 2012, pp. 181 - 191.

[4] http://www.ieee802.org/11/Reports/802.11_Timelines.htm, dostęp:11.10.2012

[5] Katulski R., Propagacja fal radiowych w telekomunikacji bezprzewodowej, WKŁ, Warszawa, 2009.

[6] Recommendation ITU-R P.1238.6, Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz.

[7] Zieliński R., Neumann P., Stochastyczne metody poszukiwania minimum funkcji, WNT, Warszawa, 1986.

[8] 802.11n IEEE Standard for Information technology.