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Optimization of the number and the distribution of high-frequency signal sources in radio networks

***Abstract**. The paper focuses on the problem of optimization of the number and distribution of high-frequency signal sources in wireless computer networks operating in complex building objects. To perform the task, the heuristic of a modified genetic algorithm and the wave propagation model in indoor building environments were used. The results of the optimization process were presented for a sample multi-storey building object with a complex geometrical and material structure.*

***Streszczenie.** W referacie podjęto tematykę optymalizacji liczby i sposobu rozmieszczenia źródeł sygnału wysokiej częstotliwości bezprzewodowych sieci komputerowych w złożonych obiektach budowlanych. W realizacji zadania wykorzystano zmodyfikowaną heurystykę algorytmu genetycznego oraz model propagacji fali w środowiskach wnętrz budynków. Wyniki optymalizacji przedstawiono dla przykładowego wielokondygnacyjnego obiektu budowlanego o złożonej strukturze geometrycznej i materiałowej. (**Optymalizacja liczby i rozmieszczenia źródeł sygnału wysokiej częstotliwości w sieciach radiowych**).*

Słowa kluczowe: optymalizacja, sieci radiowe, algorytmy genetyczne, obliczenia równoległe.
Keywords: optimization, wireless networks, genetic algorithms, parallel calculations.

Introduction

One of the conditions for efficient functioning of information society is providing the appropriate technical means that would guarantee reliable and secure transmission of large amounts of data. Currently, the additional condition of the users' mobility is imposed on such requirements. The requirements formulated above lead to constant development of wireless communication technologies, among which particular attention should be put on the use of high frequency radio waves (the so-called WiFi). This technology uses two frequency ranges: 2,4 and 5 GHz. The lower range is dominant in Europe, and the most popular of all the standards available is 802.11n. The standard makes it possible to achieve the theoretical capacity at the level of 600Mb/s (for the 5 GHz range) or 450 Mb/s (for the 2,4 GHz range), that is – values which are close to the ones obtained in networks based on copper wires (twisted-pair cable). Another version of the standard belonging to the 802.11 family which is currently being developed is supposed to guarantee the bit rate of more than 1 Gb/s. In practice, the transmission speed values are considerably lower. This is caused by technology and equipment limitations – the transmission is one-directional, it requires frequent corrections, and the transmitting-receiving devices require a certain minimum signal level for particular, discrete bit rate levels. The values that are actually achieved amount maximally to a half of the theoretical catalog data [3].

Another factor that determines transmission speed values, that is – the signal level at the receiver input, is the damping characteristics of the medium or media in which the radio wave propagates (open space, walls, ceilings, equipment). As the understanding of signal level distribution or its losses in the object analyzed is a key issue, especially at the network design stage, modeling the object analyzed as precisely as possible and the use of the appropriate propagation model pose an important problem. The implementation of the elements mentioned above makes it possible to perform numerical operations whose ultimate purpose is to optimize the number and the distribution of access points in a multi-storey building object, at the same time meeting the signal level and uniformity conditions assumed [3,6]. The task makes it possible to assure the appropriate transmission parameters, at the same time making it possible to include the technical limitations and to minimize the network installation and operation costs.

Comprehensive implementation of the objective mentioned above requires the development of an efficient optimization algorithm and the calculation of the high-frequency electromagnetic field distribution as well as the implementation of an application of the CAD/CAM type.

The characteristics of the optimization task

The process of optimizing the number and the distribution of high-frequency signal sources in 802.11 networks in complex building objects can be beneficial not only from the technical point of view (good coverage of the object with the signal level that meets the standard) but also for a number of economic aspects. This results from the fact that, apart from the technical requirements, the technical systems designed and used are more and more often expected to meet certain economic criteria. Such criteria include: decrease of investment and operation costs, or, in the case of power plants, decrease of the unit cost of electric energy production. The task solution quality criterion proposed for the optimization task to be performed which combines investment and operational cost elements is the annual average unit cost k_j defined as follows:

$$k_j = r\mathrm{K}_\mathrm{i}^{(0)} + \frac{\sum_{t=1}^{T} \mathrm{K}_e^{(t)} \left(1+p\right)^{-t}}{T} = k_i + k_e \quad (1)$$

where: r - extended reproduction rate, p – discount rate equal to the credit interest rate, t – operation year index, $\mathrm{K}_\mathrm{i}^{(0)}$ – investment cost component incurred in the so-called "year zero", $\mathrm{K}_\mathrm{e}^{(t)}$ – operation cost component incurred in year t, T – system service life.

The extended reproduction rate r is applied in the cases where the investment process is completed within one year. On the other hand, the discount factor (1+p)-t makes it possible to include the time value of money and to conduct the analyses throughout the service life period [4].

The optimization task performed is characterized by a strictly defined set of technical limitations whose satisfaction makes it possible to maintain the required transmission parameters. Those requirements include: the network bit rate (the signal level S_L at every point in the object), signal level uniformity and signal level in areas located outside of the object analyzed (data security aspects). The requirements mentioned above are of random nature and they are included with the use of the normalization process.

With the use of the annual average cost of the system kj as the assessment factor for the quality of the solution and the external penalty function in order to include the limitations imposed, the modified objective function takes the following final form:

$$\mathrm{J_m}(\mathbf{x}) = J_i(\mathbf{x}) + J_e(\mathbf{x}) + \sum_{j=1}^{N_1+N_2} F_k^{(j)}(\mathbf{x}) \tag{2}$$

where: $\mathbf{x}$ - the decision variable vector, $F_k^{(j)}$ - penalty function for the *j*-th limitation, N_1, N_2 - number of structural and functional task limitations.

The variable vector x is defined on the basis of the following factors: the access point type (AP) - x_1, AP location coordinates - x_2, x_3, x_4, AP state (operational, non-operational) - x_5, which are repeated for the maximum number N_{MAX} of access point devices assumed. The actual number of variables is $5{\cdot}N_{MAX}$ and it can reach several dozen variables in the case of large, structurally and geometrically complex multi-storey buildings. What is more, the variable vector **x** is of heterogeneous nature with respect to the variable types: real number, integer, and logical. Decision variables are included in the function (2) in a non-explicit way which increases the complexity of the task performed due to the multi-modal character of the function.

Despite the fact that it is the limit inferior of the objective function of economic nature that is searched for (2), one of the basic elements of the algorithm is control over the signal level in all the places in the building analyzed. Taking the ITU recommendations into consideration, it is possible to use one of the two high-frequency wave propagation models. In the standard model, only the number of storeys of the buildings analyzed is included [5]:

$$\mathrm{S_L} = \mathrm{P_T} - (20 \cdot \lg(\mathrm{f}) + \mathrm{N} \cdot \lg(\mathrm{d}) + \mathrm{L_f}(n) - 28)\,[\mathrm{dBm}] \tag{3}$$

where: P_T – transmitter power [dBm], f – signal frequency [MHz], N – distance-dependent power loss coefficient (N=20 for open space), d – distance between the field source and the calculation point [m], L_f – ceiling loss coefficient [dB], n – number of storeys between the source point and the calculation point.

The value of the L_f coefficient is determined on the basis of the dependency specified in the recommendation [5], which results from the physical tests performed.

In order to improve the quality of signal level calculation in complex building objects, a propagation model that constitutes a compromise between the speed and the precision of the numerical implementation was developed. It includes the electrical parameters of the air as well as of the walls and ceilings, which leads to the dependency describing the signal level expressed as follows:

$$\begin{aligned}\mathrm{S_L} &= \mathrm{P_T} - (20 \cdot \lg(\mathrm{f}) + 20 \cdot \lg(\mathrm{d} - \mathrm{d_1}) \\ &+ \sum_{\mathrm{k}=1}^{\mathrm{M}} 1636 \cdot \left(\frac{\sigma^{(\mathrm{k})}(\mathrm{f})}{\varepsilon_{\mathrm{i}}^{(\mathrm{k})}(\mathrm{f})}\right) \cdot \mathrm{d}^{(\mathrm{k})} - 28) \;\; [\mathrm{dBm}]\end{aligned} \tag{4}$$

where: k – element index (wall, ceiling), d_1 – total distance covered by the wave travelling through the walls and the ceilings, σ(k), ε(k) – material conductivity and permittivity of the element with the index k.

On the basis of the tests performed for the purpose of the calculation of signal level distribution in the optimization task performed, a model described by means of the dependency (4) was selected. Improvement in the precision of the calculations is obtained at the cost of a slight increase of the time needed to perform the analysis in relation to the model expressed by means of the formula (3). The total increase of the optimization process time for the task performed does not exceed 10%. Figure 1 presents a comparison of the signal level distribution obtained with the use of the models (3) and (4), with the assumption that the maximum power of the transmitter is 20 dBm. The calculations were performed along the line connecting the signal source (AP) located on the top storey of the building with the calculation point P located on the first storey (on the opposite side of the building). The existence of three storeys on the way of the signal was included.

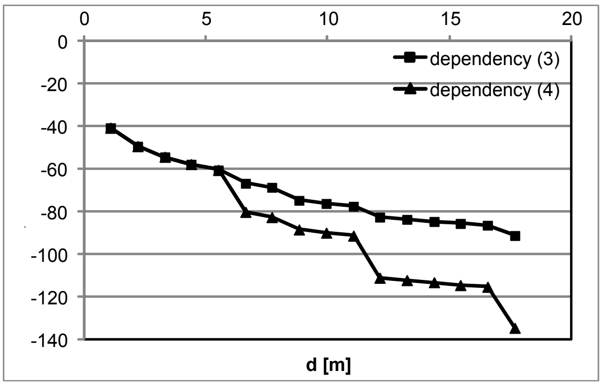
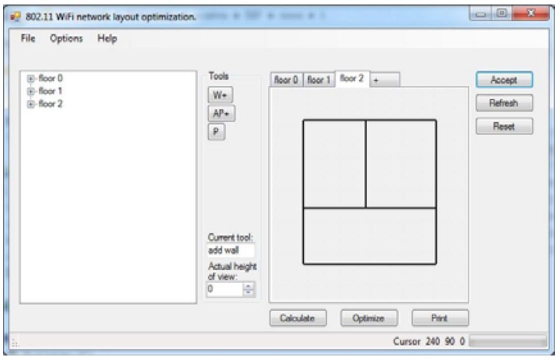


Fig. 1 High-frequency signal level as a function of the distance from the source for the models (3) and (4) – the case in which the signal travels through the walls and the ceilings of the building

The characteristics of the decision variable vector **x** and the multimodality of the function (2) determine the type of the optimization algorithm used. The population heuristic of the genetic algorithm was used to perform the numerical calculations in the task described above. Its standard form provided by Holland does not allow to solve many complex technical tasks in an efficient way [2,3]. The proposed solution to the problem is the use of a set of modifications of the standard algorithm. The following methods were used in the practical implementation of the optimization task regarding the number and the method of distribution of the access points in a multi-storey building: linear scaling of the objective function, selection with the use of the random remainder sampling method without repetition, variable vector coding with the use of Gray's code. The code sequence in the form of a single chromosome was used (positional block notation). Sequence fragments that correspond with the variables describing a particular access point are arranged one after the other. In the case of population methods, the way in which the penalty function is included is an element that has significant influence on the iteration process as well as on the final result of the optimization task. The standard approach in which external penalty is used makes it possible for the individuals to reach unacceptable values of the adaptation function which are higher than the values reached by a certain group of acceptable individuals (solutions). This leads to incorrect proportions of both types of solutions in the population and, as a consequence, causes too rapid or too slow convergence. In relation to that, it is recommended to use one of the dynamic penalty methods [4]. The Powell and Skolnick's penalty method, which prevents excessive transfer of unacceptable individuals with relatively good adaptation values to subsequent generations thanks to the determination of the penalty correction segment, with Michalewicz's modifications was used in the algorithm developed [4].

The algorithms used to calculate signal level distribution and to perform the optimization process as well as the interface of the system of the CAD type were implemented in the Visual C# language. In order to shorten the calculation time, the master-slave model was used to parallelize the genetic algorithm [1,2] with the use of TPL (Task Parallel Library) library elements in the .NET environment. Figure 2 presents the general view of the graphical environment developed for the purpose of configuring the physical structure of the building object a) and an example of the results of high-frequency signal level distribution calculations b).

a)



b)

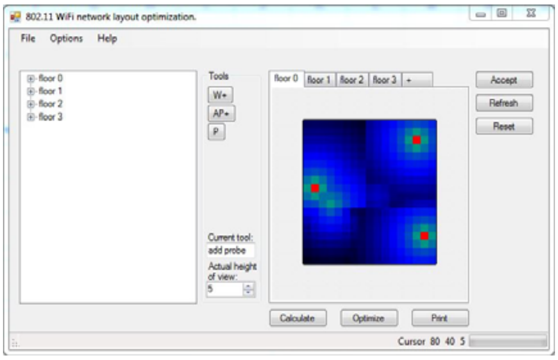


Fig. 2 The form of the graphical environment developed: a) the configuration of the building object with the wall structure – storey 2, b) sample signal level distribution

Calculation example

A sample search for the minimum number and for the distribution of high-frequency signal sources was performed for a four-storey building object with the following dimensions: 17x18x9.6 m (storey height - 2.4m). For the purpose of the calculations, it was assumed that the ceilings are 0.4m thick, and that the walls are 0.2m thick and that both elements are made of concrete.

The modified genetic algorithm heuristic described above with the following parameters: number of generations – 250, number of individuals – 50, crossover probability – 0.6, mutation probability – 0.05 was used to solve the task defined in this way.

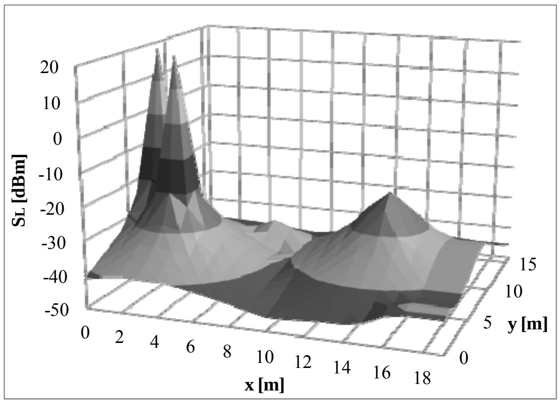
The task limitations assumed are as follows: the 802.11n 270 Mb/s signal transmission standard (minimum signal level SLMIN=-68 dBm) and signal loss uniformity at the level of 0.3. For the purpose of the calculations, it was also assumed that the acceptable number of access points distributed in the building is 30.

The calculations performed led to the determination of the optimal solution in the form of the coordinates of 12 access points minimizing the objective function (2) - table 1. Signal level distribution SL: on storey 0 (the height of 0.5 m above floor level) a) and on storey 2 (the height of 0.7 m above floor level) b) for the solution obtained is presented on Figure 3. The high-frequency wave propagation model expressed in the form of the dependency (4) was used in the calculations.

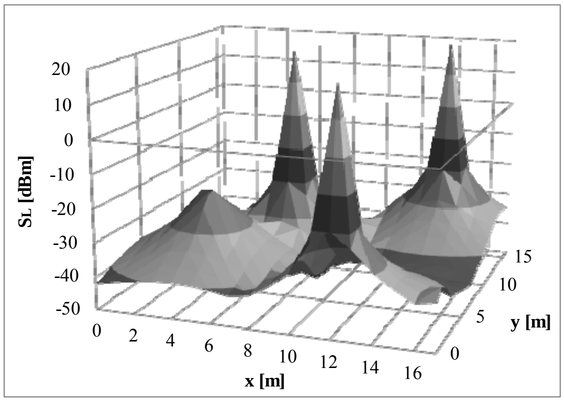
Table 1. AP distribution and device types in the optimal solution

Coordinates (x,y,z*) [m]	AP type [-]
(9.5, 7.5, 2.5)	TP-LINK TL-WA801ND
(4.5, 3.5, 7.5)	TP-LINK TL-WA701ND
(6.5, 3.5, 4.5)	TP-LINK TL-WA701ND
(1.5, 17.5, 3.5)	TP-LINK TL-WA801ND
(7.5, 1.5, 0.5)	TP-LINK TL-WA901ND
(5.5, 3.5, 0.5)	TP-LINK TL-WA801ND
(9.5, 7.5, 5.5)	TP-LINK TL-WA701ND
(1.5, 12.5, 5.5)	TP-LINK TL-WA701ND
(8.5, 14.5, 1.5)	TP-LINK TL-WA701ND
(14.5, 14.5, 5.5)	TP-LINK TL-WA801ND
(12.5, 15.5, 7.5)	TP-LINK TL-WA801ND
(5.5, 4.5, 6.5)	TP-LINK TL-WA701ND

* the z coordinate calculated in relation to the "0" storey level.



a)



b)

Fig.3. Signal loss L distribution on the storey: a) no 1 (0.5 m above ground level), b) no 3 (5.5 m above ground level)

Conclusions

The problem of optimizing the number and the distribution of high-frequency signal sources in 802.11 networks installed in buildings can be analyzed from two, seemingly distant, aspects. The first of them involves the technical parameters, e.g. the best coverage of the object with the signal whose level depends on the standard assumed, minimizing the areas outside of the building where the signal is available (limiting the wiretap risk). The second one, on the other hand, is connected with economic aspects, e.g. minimization of the investment costs, operational costs, total costs, etc. In the case of many complex technical systems, it is possible to solve the optimization task including both of those aspects. In the case of the problem considered in the present work, this task can be performed with the use of an objective function of economic character which takes the form (2) as well as a set of technical limitations.

Solving the problem of the optimal distribution of signal sources requires the performance of calculations connected with the propagation of the radio signal in building objects. An important aspect of the task is the way in which construction barriers are included. The program developed includes the electrical parameters of the barriers (walls, ceilings) and it makes it possible to achieve the required precision of signal distribution analysis within the boundaries of the object analyzed.

Due to the character of the task, the population heuristic of a genetic algorithm with the Powell and Skolnick's penalty method was used in its numerical implementation., It makes it possible to determine the global minimum, obtain satisfactory calculation repeatability and maintain the required technical parameters of the system for the structure of the decision variable vector x and for the form of the objective function assumed. It must, however, be underlined that the method assumed for the purpose of calculating signal loss distribution does not include the reflection phenomenon, which could have positive influence of the signal level inside the objects analyzed. This aspect and its influence on the results of the optimization process is going to be analyzed in further works on the problem discussed in the present paper.

The justification for such an approach to the optimization process is frequent dominance of the economic aspects. This applies both to the design phase as well as to the operation of the technical infrastructure. Minimization of the number of access points can bring tangible benefits mainly at the investment stage (minimum amount of equipment, cabling, and its accessories). A consequence of such an approach in other electrical systems (especially, higher power systems) is energy consumption minimization which is associated with a positive environmental aspect.

To sum up, it should be noted that the model developed makes it possible to obtain more precise results than the standard, simplified models, and that the application implemented which uses advanced programming technologies and numerical algorithms may serve as efficient support during the design of wireless computer networks.

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