ELECTROMAGNETIC WAVE PROPAGATION MODELING USING THE ANT COLONY OPTIMIZATION ALGORITHM

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Abstract

The Ant Colony Optimization algorithm - a multi-agent approach to combinatorial optimization problems - is introduced for a simple ray tracing performed on only an ordinary bitmap describing a two-dimensional scenario. This bitmap can be obtained as a simple scan where different colors represent different mediums or obstacles. It is shown that using presented algorithm a path minimizing the wave traveling time can be found according to the Fermat's principle. An example of practical application is a simple ray tracing performed on only an ordinary scanned bitmap of the city map. Together with the Berg's recursive model a non-line-of-sight path loss could be calculated without any need of building database. In this way the coverage predictions for urban microcells could become extremely easy and fast to apply.

Keywords

Wave propagation modeling, Ant Colony Optimization, microcell

1. Introduction

In the field of electromagnetic wave propagation modeling ray tracing technique is often utilized. Ray tracing or ray launching algorithms are very powerful providing excellent outputs. On the other hand the calculation is usually very complex and time consuming. One of the main disadvantages, especially for commercial applications, is a necessity of precise geometrical inputs, e.g. building database for urban scenarios. If an inhomogeneous environment is considered, both the algorithm and the geometrical inputs tend to be even more complicated.

In this paper a multi-agent approach to combinatorial optimization problems - the Ant Colony Optimization - is introduced for a simple ray tracing performed on only an ordinary bitmap describing a two-dimensional scenario. This bitmap can be obtained as a simple scan where different colors represent different mediums or obstacles. Using the presented algorithm the fastest path for a ray - electromagnetic wave - can be found according to the Fermat's principle. Thanks to the very easy-to-obtain inputs the wave propagation modeling could become, for selected tasks, simple and fast to apply.

2. Ant Colony Optimization

The Ant Colony Optimization was proposed by Dorigo [1]. This multi-agent approach can be used for various combinatorial optimization problems. The algorithms were inspired by the observation of real ant colonies. Ants are social insects living in colonies with interesting foraging behavior. In particular, an ant can find shortest paths between food sources and a nest. While walking from food sources to the nest and vice versa, ants deposit on ground a substance called pheromone, forming a pheromone trail. Ants can smell pheromone and, when choosing their way, they tend to choose paths marked by strong pheromone concentrations. It has been shown that this pheromone trail following behavior employed by a colony of ants can give rise to the emergence of the shortest paths. This phenomenon is explained in Fig. 1.

In Fig. 1a ants walk between two points via unobstructed path. Both the marching ants (top of the picture) and corresponding pheromone trail (bottom of the picture) are displayed. When an obstacle breaks the path (Fig. 1b), ants try to get around obstacle randomly choosing either way. If the two paths encircling the obstacle have different lengths, more ants pass shorter route on their continuous pendulum motion in particular time interval. While each ant keeps marking its way by pheromones the shorter route attracts more pheromone concentrations and consequently more and more ants choose this route. This feedback leads soon to final stage in Fig. 1c, where entire ant colony uses the shortest path. There are many variations of the ant colony algorithm applied on various classical optimization problems. Many references can be found in [2].

3. Description of the Algorithm

The algorithm is based on the Ant Colony System (ACS) technique [3] originally proposed for Traveling Salesman Problem. It was modified for needs of the wave propagation simulation. The adapted algorithm can be described in five steps:

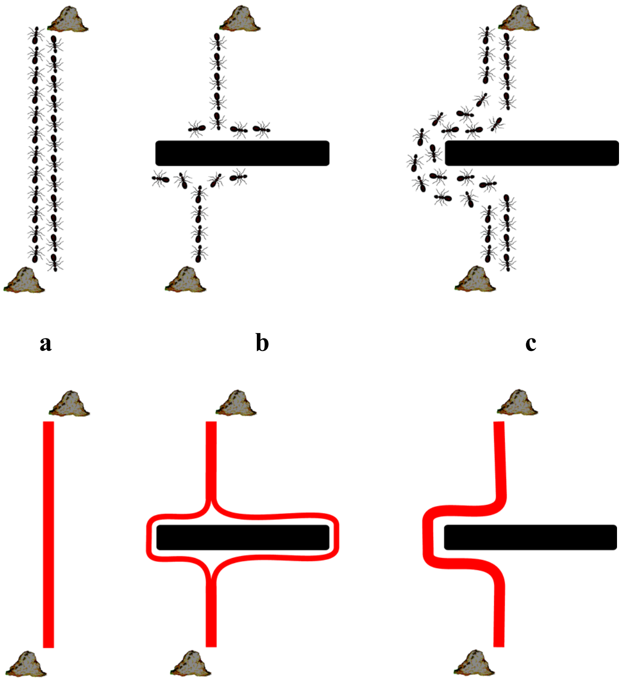

Fig. 1 Ant Colony Optimization: ants searching the shortest route using a pheromone trail.

3.1 Step 1 - A Generation of an Undirected Graph

An undirected graph $G = (N, A)$, where N is set of nodes and A the set of arcs connecting the nodes, and two nodes N_1 and N_2 to be connected by the required fastest ray have to be defined in the first step. The nodes N are easily generated as a uniform grid applied on an input pixel bitmap describing the propagation environment. The density of the nodes determines the precision of a solution but also memory and computation time demands of the algorithm. Then arcs A interconnect all the nodes of the graph - one with each other. Using simple raster graphics procedures all the nodes and arcs interfering with colored elements, which represent buildings or other obstacles (e.g. black color), are eliminated. In addition, each arc must traverse through only a single medium, i.e. only one color in the bitmap. Appropriate wave traveling time is assigned to each arc based on its physical length and the propagation medium. The graph generation is shown in Fig. 2, where a very sparse grid of nodes was used as an illustration. All arcs A of the graph G are initialized with a small amount of pheromone τ_0, which is a value corresponding to the direct wave traveling time between N_1 and N_2 considering the wave speed in vacuum.

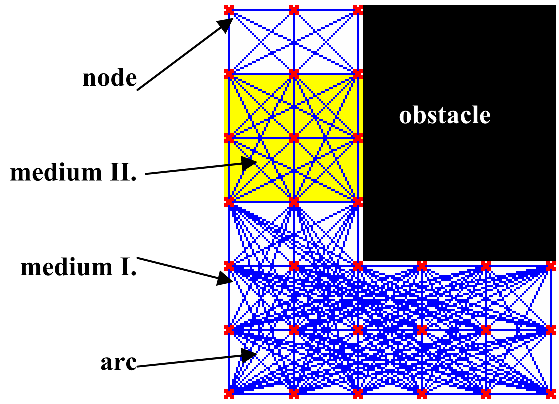

Fig. 2 Illustration of an undirected graph generation.

3.2 Step 2 - A Colony of Ants is Launched

In the second step C ants are sequentially launched from N_1. C is a number of ants in the colony. Each ant walks pseudo-randomly from node to node via connecting arcs as far as the N_2 or dead end is reached (Fig. 3).

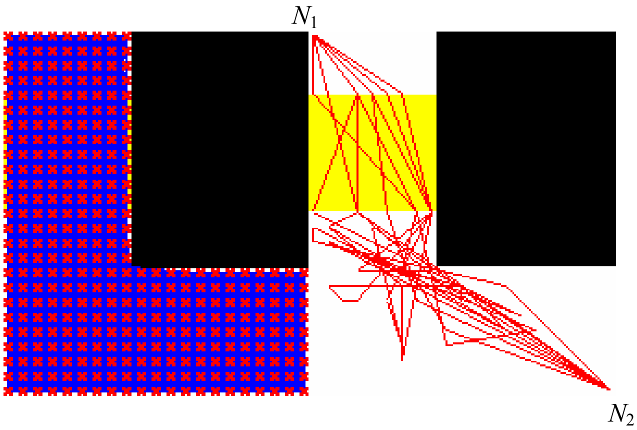

Fig. 3 Nodes and arcs of an undirected graph and ants' pseudo-random motion in the graph.

When deciding which arc to go from a specific node, each i-th arc leading from the node is assigned a probability:

$$p_i = \frac{\tau_i \eta_i^{\beta}}{\sum_i \tau_i \eta_i^{\beta}} \qquad (1)$$

where τ_i is the pheromone concentration on the i-th arc, η_i is an a priori available heuristic value for the i-th arc - a wave traveling time to appropriate connected node and then continuing directly to N_2 considering the wave speed in vacuum, and β is a parameter determining the relative influence of the heuristic information. This parameter plays a key role for the algorithm performance.

Then a random number q between 0 and 1 is generated. If $q < q_0$, where q_0 is another parameter of the algorithm, the ant chooses to go via an arc with the highest probability p_i. Otherwise random selection of the arc based on the probability distribution (1) is accomplished. The previously visited arcs are excluded from the selection.

After having crossed the selected i-th arc during the ant's tour construction a local update rule is immediately applied to the pheromone concentration on the arc:

$$\tau_i = (1-\rho)\,\tau_i + \rho\tau_0 \tag{2}$$

where ρ is a parameter $0 \leq \rho \leq 1$. The effect of the local updating rule is to make already chosen arc less desirable for a following ant. In this way more route variations can be explored.

3.3 Step 3 - An Optimization of Ants' Paths and the Best Ant Selection

After all ants from the colony finish their routs the most successful ant - the ant with the fastest path from N_1 to N_2 - is selected to update the pheromone trails in the following step. Before the selection a deterministic optimization is performed on all of the ants' paths. This very fast and simple procedure tries to eliminate unnecessary nodes on an ant's route. It is based on the following principle: if N_a, N_b and N_c are consecutive nodes, the existence of a direct connection between N_a and N_c is tested. If such an arc exists, the N_b is excluded from the path (Fig. 4). Overall performance of the ACS algorithm is significantly improved using this technique.

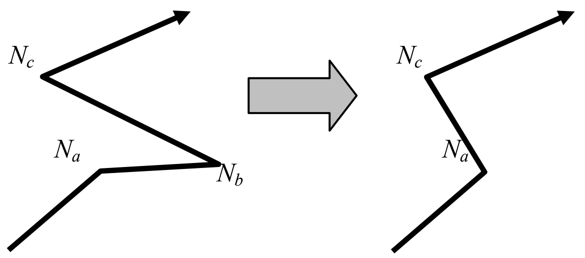

Fig. 4 Deterministic optimization of an ant's path

3.4 Step 4 - A Global Update of Pheromone Trails

All arcs of the graph G are updated using a global update rule:

$$\tau_i = (1-\alpha)\,\tau_i + \alpha\tau_T \tag{3}$$

where α is a parameter ($0 \leq \alpha \leq 1$) determining the evaporation of pheromone concentrations and

$$\tau_T = \begin{cases} T, & \text{for the } i\text{-th arc visited by the best ant.} \\ 0, & \text{otherwise.} \end{cases}$$

T is the best ant's traveling time, which is a sum of wave traveling times assigned to all visited arcs.

In homogenous environments, where the wave speed is the same throughout the map, a value inversely proportional to the path length of the best solution can be used for the pheromone update. In this case the shortest path instead of the fastest path is searched. It leads to the same results in homogenous mediums.

There are two different ways to choose the best ant that is allowed to perform the global updating. In the "global-best" method only the ant that did the fastest route since the very beginning of the optimization process is selected. In the "iteration-best" method always the best ant from the colony of C ants deposits the pheromones despite of previous iterations.

Whereas the global-best strategy was preferred in [3] for solving Traveling Salesman Problem, in all presented simulations iteration-best method was applied. When global-best strategy was used for the ray tracing, a frequent convergence to local minimums of the optimization algorithm was observed.

3.5 Step 5 - A Termination of the Algorithm

Steps 2 to 4 are repeated for a fixed number of iterations or as long as the desired solution is reached. After the termination of the algorithm a stored solution of the very best ant indicates the fastest path between N_1 and N_2.

4. Evaluation of the Algorithm

As shown above there are five basic parameters controlling the ASC algorithm: number of ants C, q_0 and β for pseudo-random route selection in (1), ρ for the local update rule in (2), and α for the global update rule in (3). A software tool was developed to test and evaluate the algorithm. Examples of screenshots are shown in Fig. 5 and Fig. 7. As default starting values the parameters from [3] were used: C = 10, q_0 = 0.9, β = 2.0, ρ = 0.1, and α = 0.1. Large set of different parameters was tested on simple scenarios to find the optimal values for our kind of problems. Following values were established as the optimum: C = 50, q_0 = 0.5, β = 3.0, ρ = 0.2, and α = 0.2.

The heuristic information η_i together with the parameter β from (1) was found of crucial importance for the algorithm. Results of the search process for four different sets of parameters are shown in Fig. 6.

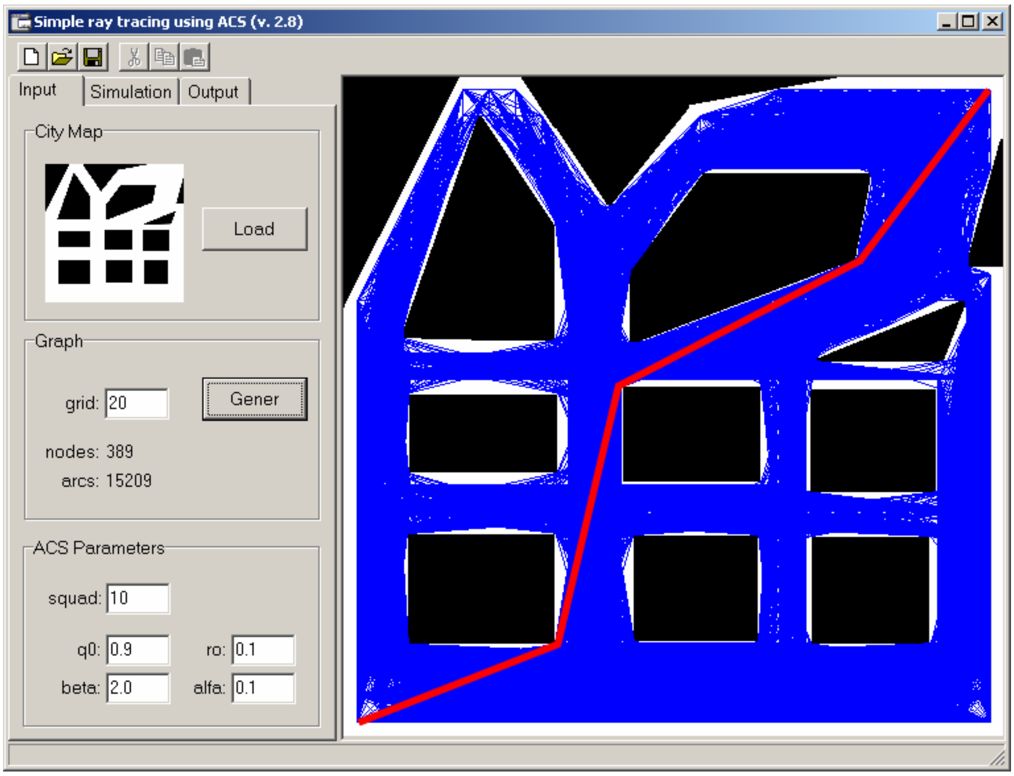

Fig. 5 A screenshot of the software simulation tool for the ACS algorithm testing - the shortest path search in urban scenario (in the 2D map picture the found ray, buildings, and arcs of the graph are drawn).

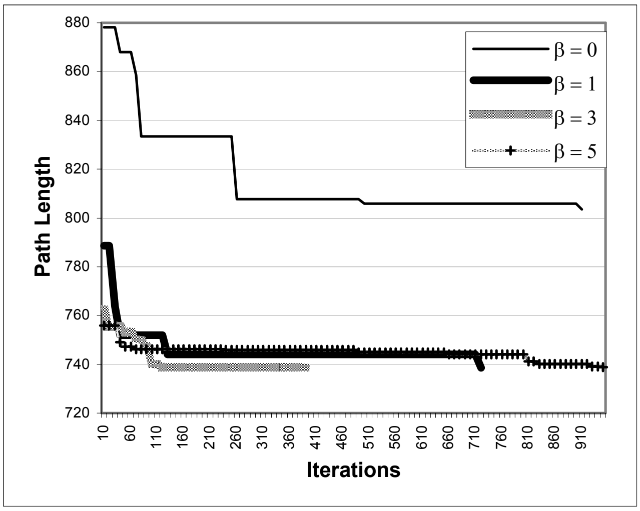

Fig. 6 The shortest path search process (corresponding to the input scenario in Fig. 5) for four different sets of parameters: C = 50, q_0 = 0.5, β = 0.0, 1.0, 3.0, and 5.0, ρ = 0.2, α = 0.2.

In this case the influence of β is demonstrated. For β = 3 the global solution was found very quickly. When the value is significantly increased (β = 5) or decreased (β = 1), the same solution is reached, but the algorithm convergence is much slower. It can be seen that for β = 0, which means the heuristic information η_i in (1) is completely ignored, the global optimum was not found at all. Other parameters were not so fundamental for the optimization. For instance, the number of ants C = 50 is a compromise: the higher is the value of C the higher is the certainty that the global solution will be found, but, at the same time, the longer is the computation time.

5. Simple Ray Tracing in Inhomogeneous Environment

As an example of a practical application of the algorithm, Fig. 7 shows two simple scenarios with three different mediums with a different wave propagation velocity $v_1 > v_2 > v_3$ (as it is marked in the pictures). The mediums are differentiated by colors in the input bitmap of the optimization algorithm. A solid line represents a result of the simulation: the fastest path of the wave from lower-left corner to upper-right corner of the bitmap (the path that minimizes the wave traveling time). The Fermat's principle can be nicely demonstrated. The global solution was usually obtained within 50 iterations for both examples. The number of arcs in the graphs was more than 10,000 and 71,000, respectively.

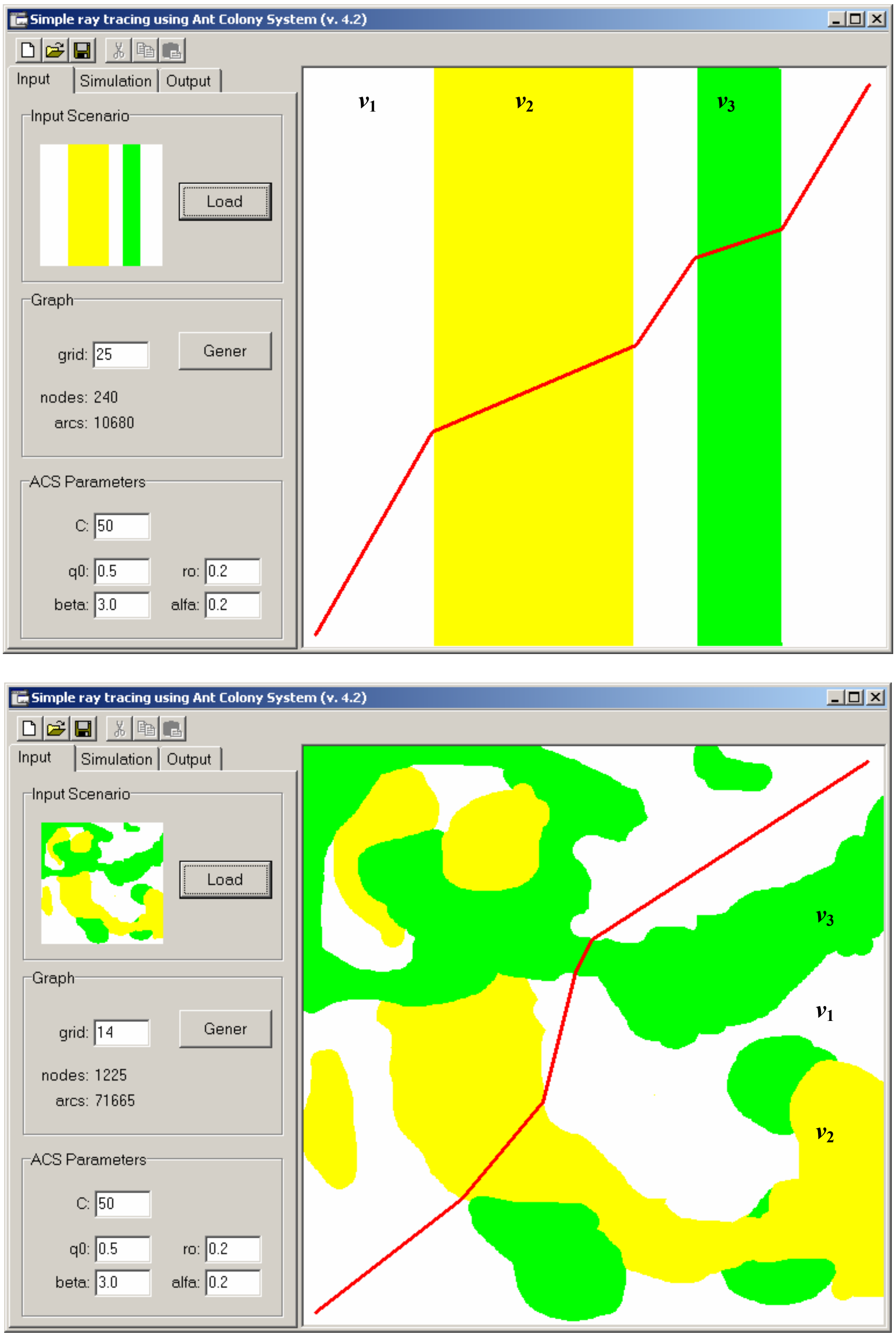

Fig. 7 Examples of a simple ray tracing in inhomogeneous environments described by a bitmap using the ACS algorithm. The traveling time of the wave is minimized according to the Fermat's principle.

5.1 Path-Loss Calculation in Microcells using the Berg's Recursive Model

One of the practical applications of the algorithm for a propagation prediction in microcells is introduced in [4]. Microcellular structure is mostly demanded for new wireless personal communication systems, such as UMTS. Empirical propagation models widely used in macrocells cannot be utilized in microcells. The nature of wave propagation in urban microcells requires different approach. Mostly the deterministic ray tracing techniques were adopted. As it was already mentioned, while the results of the deterministic modeling are excellent (precision, wide-band outputs) the input requirements are very extensive. Building database incl. electrical parameters of used materials has to be defined. That is why there is a challenge to explore alternative ways of the signal propagation prediction.

Semi-deterministic approach for street microcells - recursive model - was introduced by J-E. Berg [5]. Model does not require knowledge of building materials but only a plan view building database is needed. The shortest path along streets is determined among buildings between a base station and a mobile antenna. A simple two-dimensional geometrical ray tracing technique can be used. Path is break down into a number of straight segments interconnected by nodes. The "illusory" distance is obtained recursively as function of a real length of the segments and angle of segments crossings in nodes. It means each time the path bends illusory distance is lengthened in comparison to the physical length. Then a very simple empirical formula is applied on the illusory distance to calculate the total path loss. A detailed description of the model can be found in [5]. The model was also included to [6].

Using the presented ACS algorithm together with the recursive model, a non-line-of-sight path loss could be calculated without any need of building database. Classical ray tracing would require some kind of information on buildings' locations and shapes. If the ACS algorithm is applied to find the desired shortest segmented path along streets, only a bitmap (scan of the city map) can be used as an input. In this way the coverage predictions for urban microcells could become extremely easy and fast to apply. Fig. 5 demonstrates the shortest path search among several obstacles, which can represent buildings in microcell.

6. Summary

For a simple two-dimensional ray tracing in inhomogeneous mediums a new algorithm based on the Ant Colony Optimization was introduced. A common bitmap can be used as an input describing even complicated environments. Practical application for coverage predictions in microcells, which is based on two techniques originated in very different fields of application, was presented. The Ant Colony Optimization together with the Berg's recursive model enables non-line-of-sight path loss calculations without any need of building database.

As indicated above, first simulations for simple urban scenarios proved a very promising efficiency and usefulness of the algorithm. The work continues tuning and evaluating the method on more complex scenarios. Obviously there are other propagation prediction applications where the presented ACS algorithm can be utilized instead of classical ray tracing.

Other well known deterministic algorithms can be used for the introduced idea of tracing a ray in an undirected graph as well. As a reference Dijkstra's Algorithm [7] was implemented. It leads always to global best solution but it is not so efficient for dense and large graphs. More details about the graph theory and various relevant algorithms can be found in [7] including many references.

Acknowledgements

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Pavel PECHAČ graduated at the Czech Technical University in Prague, Faculty of Electrical Engineering in 1993. He received his Ph.D. in Radioelectronics in 1999 at the Department of Electromagnetic Field. He is with the department as an associate professor. His research interests have been mainly in the field of the electromagnetic waves propagation predictions for mobile wireless systems.