# A Study on Performance of Hill Climbing Heuristic Method for Router Placement in Wireless Mesh Networks

**Evjola Spaho, Alda Xhafa, Donald Elmazi, Fatos Xhafa and Leonard Barolli**

**Abstract** Wireless Mesh Networks (WMNs), also referred to as a form of wireless ad hoc network are in fact one particular type of Wireless Sensor Networks (WSNs), whose topology can vary from a simple star network to an advanced multi-hop wireless mesh network. The main topological feature in this case is that nodes are organized in a mesh topology, making WMNs a reliable infrastructure through redundancy of multi-hop communications. The main issue of WMNs is to achieve network connectivity and stability as well as Quality of Service (QoS) in terms of user coverage. This problem is very closely related to the family of node placement problems in WMNs, among them, the mesh router mesh nodes placement. In this work we present some optimization problems in WMNs and Hill Climbing (HC) heuristic method for solving mesh router node placement near-optimally. We formulate the optimization problems using bi-objective optimization models. Thus, for the mesh router nodes placement, the bi-objective optimization problem is obtained consisting in the maximization of the size of the giant component in the mesh routers network (for measuring network connectivity) and that of user coverage. Some computational results are presented and discussed for the HC method, which is an effective local search method.

**Keywords** WMNs · WSNs · Hill Climbing · Heuristic method · Size of giant component · Covered mesh clients

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## 1 Introduction

Wireless Mesh Networks (WMNs) [1, 2] are gaining a lot of attention because of their low cost nature that makes them attractive for providing wireless Internet connectivity. A WMN is dynamically self-organized and self-configured, with the nodes in the network automatically establishing and maintaining mesh connectivity among themselves (creating, in effect, an ad hoc network). This feature brings many advantages to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage. Moreover, such infrastructure can be used to deploy community networks, metropolitan area networks, municipal and corporative networks, and to support applications for urban areas, medical, transport and surveillance systems. The main issue of WMNs is to achieve network connectivity and stability as well as Quality of Service (QoS) in terms of user coverage. This problem is very closely related to the family of node placement problems in WMNs, among them, the mesh router mesh nodes placement. Node placement problems have been long investigated in the optimization field due to numerous applications in location science (facility location, logistics, services, etc.) and classification (clustering) [1, 3–6].

WMNs (also referred to as a form of wireless ad hoc network) are in fact one particular type of Wireless Sensor Networks (WSNs) [7], whose topology can vary from a simple star network to an advanced multi-hop wireless mesh network. The main topological feature in this case is that nodes are organized in a mesh topology, making WMNs a reliable infrastructure through redundancy of multi-hop communications.

Different optimization problems can be formulated based on the objectives to optimize and a set of different constraints, such as topological restrictions, battery restrictions, QoS requirements, etc. Some optimization problems are related to minimize the cost of the WMN, such as minimizing the number of mesh router nodes to deploy, while others focus on the WMN performance, such as computing optimal placement of an a priori fixed number of mesh router nodes. The presence of many objectives is in fact a main challenge. These objectives include minimizing the number of mesh routers, maximizing network connectivity, maximizing user coverage, minimizing energy consumption (especially in wireless and mobile networks), minimizing communication delay, maximizing throughput, minimizing deployment cost, etc. And, additionally, there could be certain constraints to take into account such as topological restrictions of the geographical area, interference model, etc. It should also be noted that some of the objectives are contradicting, in the sense that trying to optimize some objective goes in detriment to the optimization of another objective.

Several optimization problems are showing their usefulness to the efficient design of WMNs. These problems are related, among others, to optimizing network connectivity, user coverage and stability. The resolution of these problems turns out to be crucial for optimized network performance. Most important optimization problems in WMNs deal with computing optimal placement of nodes (mesh router nodes, gateways and distribution of mesh client notes), so that network performance is optimized. However, node placement problems are known for their hardness to solve to optimality and therefore heuristics methods are used to nearoptimally solve such problems [8–12].

Given the complexity of node placement problems, most authors have proposed the use of simple heuristic methods or more advanced search methods such as Genetic Algorithms (GAs). So far, only single optimization versions have been considered for the problem. We have considered the bi-objective case, and plan to extend the model to integrate more objectives resulting in a multi-objective optimization model where different objectives could as well be contradicting ones.

In this work, we use HC heuristic method for solving node placement problems in WMNs. We exemplify the applicability of heuristic methods for the case of solving mesh router nodes problem near-optimally.

The rest of the chapter is organized as follows. In Sect. 2 are presented the application scenarios of WMNs. The mesh router nodes placement problem is defined in Sect. 3. In Sect. 4 are described resolution methods for solving nodes placement problem and an introduction of Hill Climbing (HC) algorithm for mesh router placement. In Sect. 5 is described the Web Interface for simulating mesh router nodes placement. The simulation results are given in Sect. 6. In Sect. 7, we give conclusions and future work.

## 2 Application Scenarios of WMNs

There are a number of application scenarios for which the use of WMNs is a very good alternative to offer connectivity at a low cost.

### *2.1 Neighboring Community Networks*

In a community, the usual solution is to deploy ADSL or cable. However, there are a number of limitations that WMNs can improve as shown in following.

- A large percentage of areas between the houses could not receive wireless services.
- A broadband gateway between different houses could not be shared and wireless services should be established individually.
- A single path to each neighbor can communicate with the rest of neighbors or with the outside.

### 2.2 Corporative Networks

This scenario corresponds to having a small network for an office or a medium sized network for all offices of a building or even a network to communicate offices located in different buildings. Other similar scenarios include airports, hotels, shopping centers or sports centers.

### 2.3 Metropolitan Area Networks

Deploying WMNs in metropolitan areas has a number of advantages. The physical layer provides a higher average transmission to any cellular network and need not depend on a wiring. Also, deploying such infrastructure is much cheaper than cable or fiber and can be easily and rapidly deployed in areas with few resources, which have never had any network before.

### 2.4 Other Scenarios

There are many more scenarios for which WMNs can be used. We mention some of them in following [3].

- *Transportation Systems* Provide information services to passengers, remote monitoring of vehicle safety and communications by the driver.
- *Automatic Control Buildings* In buildings there are several electrical devices to be controlled, including light, elevator, air conditioning, and so on.
- *Medical and Health Systems* In a hospital information monitoring and diagnosis must be transmitted from one room to another.
- *Surveillance* In corporate buildings, shopping malls and stores need broadband data transmission (images and videos basically) for monitoring and surveillance purposes.

## 3 Mesh Router Nodes Placement Problem in WMNs

Different optimization problems can be formulated based on the objectives to optimize and a set of different constraints, such as topological restrictions, battery restrictions, QoS requirements, etc. Some optimization problems are related to minimize the cost of the WMN, such as minimizing the number of mesh router nodes to deploy, while others focus on the WMN performance, such as computing optimal placement of an a priori fixed number of mesh router nodes [13–15].

The presence of many objectives is in fact a main challenge. These objectives include minimizing the number of mesh routers, maximizing network connectivity, maximizing user coverage, minimizing energy consumption (especially in wireless and mobile networks), minimizing communication delay, maximizing throughput, minimizing deployment cost, etc. And, additionally, there could be certain constraints to take into account such as topological restrictions of the geographical area, interference model, etc. It should also be noted that some of the objectives are contradicting, in the sense that trying to optimize some objective goes in detriment to the optimization of another objective.

In our work, we consider the optimization of mesh router nodes placement in WMNs. In this problem, we are given a grid area arranged in cells where to distribute a number of mesh router nodes and a number of mesh client nodes of fixed positions (of an arbitrary distribution) in the grid area. The objective is to find a location assignment for the mesh routers to the cells of the grid area that maximizes the network connectivity and client coverage. Network connectivity is measured by the size of the giant component of the resulting WMN graph, while the user coverage is simply the number of mesh client nodes that fall within the radio coverage of at least one mesh router node.

An instance of the problem consists as follows.

- $N$ mesh router nodes, each having its own radio coverage, defining thus a vector of routers.
- An area $W \times H$ where to distribute $N$ mesh routers. Positions of mesh routers are not pre-determined, and are to be computed.
- $M$ client mesh nodes located in arbitrary points of the considered area, defining a matrix of clients.

It should be noted that network connectivity and user coverage are among most important metrics in WMNs and directly affect the network performance.

In this work, we have considered a bi-objective optimization in which we first maximize the network connectivity of the WMN (through the maximization of the size of the giant component) and then, the maximization of the number of the user coverage.

For optimization problems having two or more objective functions, two settings are usually considered: the hierarchical and simultaneous optimization. In the former, the objectives are classified (sorted) according to their priority. Thus, for the bi-objective case, one of the objectives, say *f1*, is considered as a primary objective and the other, say *f2*, as secondary one. The meaning is that we first try to optimize *f1*, and then when no further improvements are possible, we try to optimize *f2* without worsening the best value of *f2*. In the case of WMNs, the hierarchical approach is used due achieving network connectivity is considered more important than user coverage. It should be noted that due to this optimization priority, some client nodes may not be covered due the user coverage is less optimized.

## 4 Resolution Methods for Solving Nodes Placement Problem

Given the complexity of node placement problems, most authors have proposed the use of simple heuristic methods or more advanced search methods such as Genetic Algorithms [6, 14, 16–21]. We exemplify the applicability of heuristic methods for the case of solving mesh router nodes problem. We have considered a local search method, HC.

### *4.1 Exact Algorithms*

**Brute force algorithms** These algorithms, also known as enumerative algorithms, can be used to find the optimal solutions (e.g. [14]); however, the solution space of the problem is in general exponentially large and such methods fail to find a solution in reasonable time as they make an exhaustive search of the solution space.
**Integer Linear Programming** Mathematical programming has been among most used methods in combinatorial optimizations. Its version of integer variables (Integer Linear Programming ILP) has shown useful in modelling and resolution of node placement problems in general and that of node placement in WMN (see e.g. [3, 13]). The main drawback again is that solving an ILP is intractable and can be solved only for small or moderate size instances of the problem.

### *4.2 Local Search Algorithms*

Local Search (LS) algorithms are among the best candidates for solving mesh node placement problems due to their efficiency and simplicity. LS has been used in [16] for the mesh node placement. We present next the application of HC for solving mesh router nodes problem.

**Hill Climbing Algorithm for Mesh Router Node Placement** We present here the particularization of the Hill Climbing algorithm (see Algorithm 1) for the mesh router node placement problem in WMNs.

**Algorithm 1**: Hill Climbing algorithm for maximization of $f$ (fitness function).

```
Start: Generate an initial solution s_0;
s = s_0; s* = s_0; f* = f(s_0);
repeat
  Movement Selection: Choose a movement m = select_movement(s);
  Evaluate & Apply Movement:
  if δ(s, m) ≥ 0 then
    s' = apply(m, s);
    s = s';
  end if
   Update Best Solution:
   if f(s') > f(s*) then
     f* = f(s');
     s* = s';
   end if
   Return s*, f*;
until (stopping condition is met)
```

*Initial solution* The algorithms starts by generating an initial solution either random or by *ad hoc* methods [22].

*Evaluation of fitness function* An important aspect is the determination of an appropriate objective function and its encoding. In our case, the fitness function follows a hierarchical approach in which the main objective is to maximize the size of giant component in WMN.

*Neighbor selection and movement types* The neighborhood $N(s)$ of a solution $s$ consists of all solutions that are accessible by a local move from $s$. We have considered three different types of movements. The first, called *Random*, consists in choosing a router at random in the grid area and placing it in a new position at random. The second move, called *Radius*, chooses the router of the largest radio and places it at the center of the most densely populated area of client mesh nodes (see Algorithm 2). Finally, the third move, called *Swap*, consists in swapping two routers: the one of the smallest radio situated in the most densely populated area of client mesh nodes with that of largest radio situated in the least densely populated area of client mesh nodes. The aim is that largest radio routers should serve to more clients by placing them in more dense areas.

We also considered the possibility to combine the above movements in sequences of movements. The idea is to see if the combination of these movements offers some improvement over the best of them alone. We called this type of movement *Combination*:

$$<Rand_1, \ldots, Rand_k; Radius_1, \ldots, Radius_k; \\ Swap_1, \ldots, Swap_k>,$$

where $k$ is a user specified parameter.

*Acceptability criteria* The acceptability criteria for newly generated solution can be done in different ways (simple ascent, steepest ascent, or stochastic). In our case, we have adopted the simple ascent, that is, if $s$ is current solution and $m$ is a movement, the resulting solution $s'$ obtained by applying $m$ to $s$ will be accepted, and hence become current solution, iff the fitness of $s'$ is at least as good as fitness of solution $s$. In terms of $\delta$ function, $s'$ is accepted and becomes current solution if $\delta(s, m) \geq 0$. It should be noted that in this definition we are also accepting solutions that have the same fitness as previous solution. The aim is to give chances to the search to move towards better solutions in solution space. A more strict version would be to accept only solutions that strictly improve the fitness function ($\delta(s, m) > 0$).

**Algorithm 2**: Radius movement.

1: **Input**: Values $H_g$ and $W_g$ for height and width of a small grid area.
2: **Output**: New configuration of mesh nodes network.
3: Compute the most dense $H_g \times W_g$ area and $(x_{dense}, y_{dense})$ its central cell point.
4: Compute the position of the router of largest radio coverage $(x_{largest\_cov}, y_{largest\_cov})$.
5: Move router at $(x_{largest\_cov}, y_{largest\_cov})$ to new position $(x_{dense}, y_{dense})$.
6: Re-establish mesh nodes network connections.

## 5 Web Interface for Simulating Mesh Router Nodes Placement

The Web application [23] follows a standard Client-Server architecture and is implemented using LAMP (Linux + Apache + MySQL + PHP) technology (see Fig. 1). Remote users (clients) submit their requests by completing first the parameter setting. The parameter values to be provided by the user are classified into three groups, as follows.

**Parameters related to the problem instance** These include parameter values that determine a problem instance to be solved and consist of number of router nodes, number of mesh client nodes, client mesh distribution, radio coverage interval and size of the deployment area.

**Parameters of the resolution method** Each method has its own parameters. For instance, Simulated annealing has a starting temperature while Genetic Algorithm has population size, etc.

**Execution parameters** These parameters are used for stopping condition of the resolution methods and include number of iterations and number of independent runs. The former is provided as a total number of iterations and depending on the method is also divided per phase (e.g., number of iterations in a exploration). The later is used to run the same configuration for the same problem instance and parameter configuration a certain number of times.

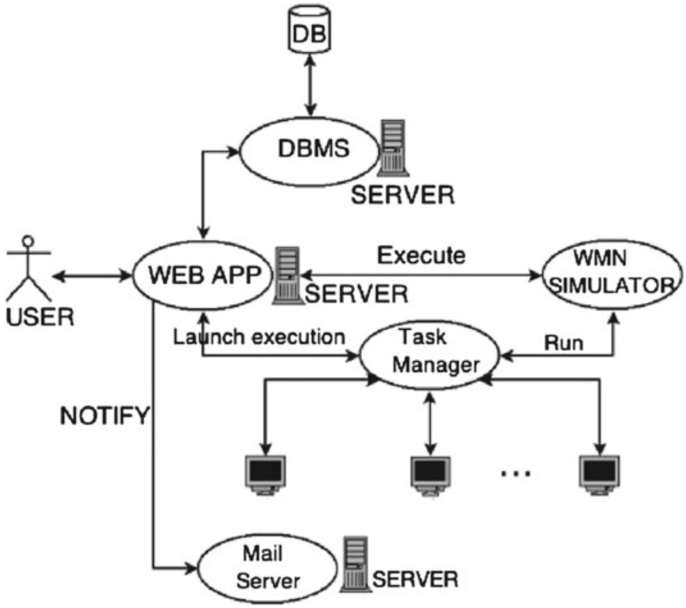



**Fig. 1** Web application architecture

## *5.1 Use Cases*

**Simulation of different mesh client node positions** Client mesh node positions can be chosen from different probability distributions so as to simulate different cases in real life. For instance, positions of stationary client mesh nodes distributed along roadside can be generated using the Exponential distribution while positions of stationary client mesh nodes concentrated at different points in the area can be generated from Weibull distribution.

**Simulation of different radio coverage for mesh router nodes** Mesh router nodes can have different coverage. The interface allows to select an interval for radio coverage and radio coverage are generated for each router uniformly at random from that interval.

**Simulation of different number of mesh routers** The number of mesh router nodes is an input to resolution methods. Their positions in the deployment area are to be computed by the resolution methods subject to optimizing WMN metrics.

**Simulation of different number of mesh clients** The number of mesh client nodes is introduced in input as well. Once this number is provided, the simulator generates the positions of the mesh client nodes using one of the probability distributions (uniform, normal, exponential, Weibull).

## 6 Simulation Results

The simulation parameters and their values are shown in Table 1. In this work, we considered a small grid area with size (32 × 32). The number of mesh routers is considered 16 and the number of mesh clients 48. We used Normal, Uniform, Exponential and Weibull distribution of mesh clients. For the simulations we used the combination method. The total number of iterations is considered 5000 and the iterations per phase is considered 100. We carried out many simulations to evaluate the performance of WMNs.

In Fig. 2 are shown the computational results for Normal distribution. In Fig. 2a are shown the simulation results for size of giant component versus number of generations. After few generations, HC algorithm achieved to establish a network of all routers connected.

The number of covered mesh routers versus the number of generations is shown in Fig. 2b. In Normal distribution, mesh clients are concentrated at the center of the grid area and the position of mesh routers becomes easy to calculate. The maximal number of covered mesh clients is 43. Figure 2c visualize the position of mesh routers, mesh clients, their connectivity and coverage.

For the Uniform distribution (see Fig. 3), mesh clients are scattered inside the grid area and the positioning of mesh routers becomes difficult. The size of giant component is not maximized and the number of covered mesh clients is 27. In order to cover more mesh clients, the number of mesh routers should be increased.

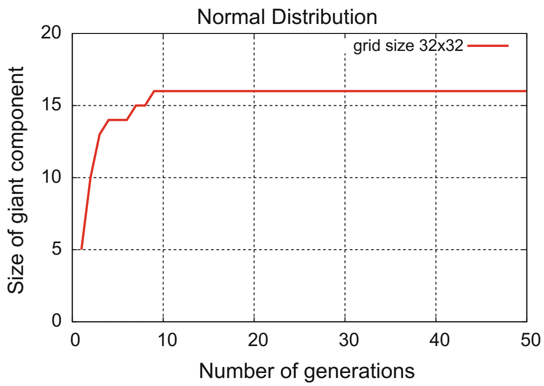
The simulation results for exponential distribution are shown in Fig. 4. Exponential distribution of mesh clients is similar with a real scenario where stationary mesh clients are distributed along the roadside. For this scenario, all 16 mesh routers are connected with each other and 37 mesh clients are covered.

For Weibull distribution (see Fig. 5) the giant component is maximal and the covered mesh clients are 42.

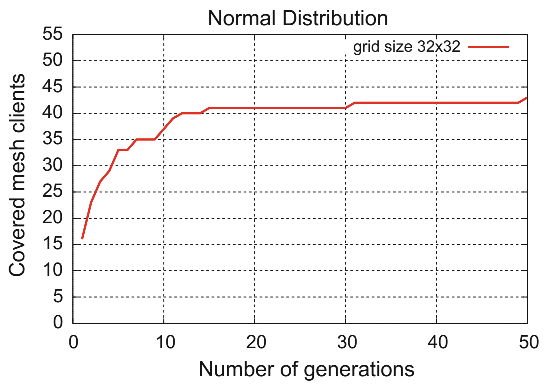
**Table 1** Simulation parameters and their values

| Parameters | Values |
|---|---|
| Clients distribution | Normal, uniform, exponential, Weibull |
| Number of mesh clients | 48 |
| Number of mesh routers | 16 |
| Grid size | 32 × 32 |
| Router radius | 2 |
| Iterations per phase | 100 |
| Total number of iterations | 5000 |
| Number of generations | 50 |
| Apply method | Combination |

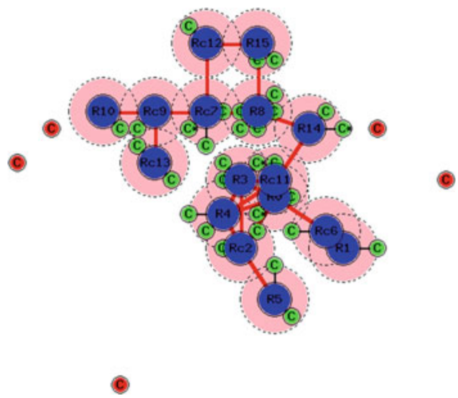
**Fig. 2** Simulation results for normal distribution




(a) Size of Giant Component

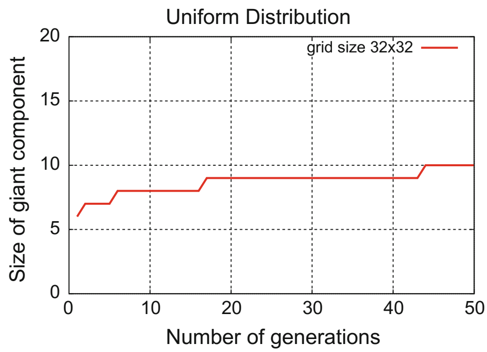



(b) Number of covered mesh clients



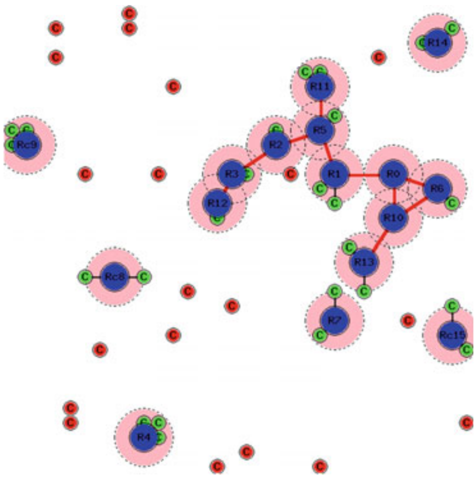

(c) Visualization

**Fig. 3** Simulation results for uniform distribution



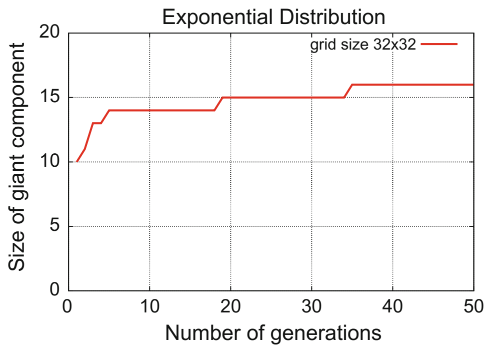

(a) Size of Giant Component


(b) Number of covered mesh clients

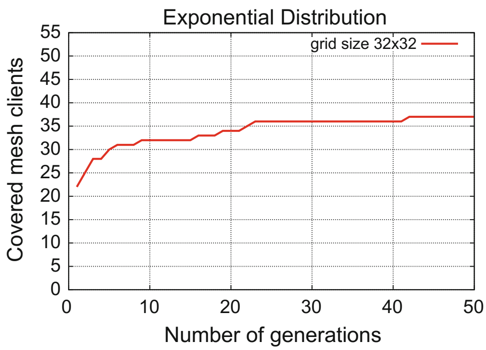


(c) Visualization

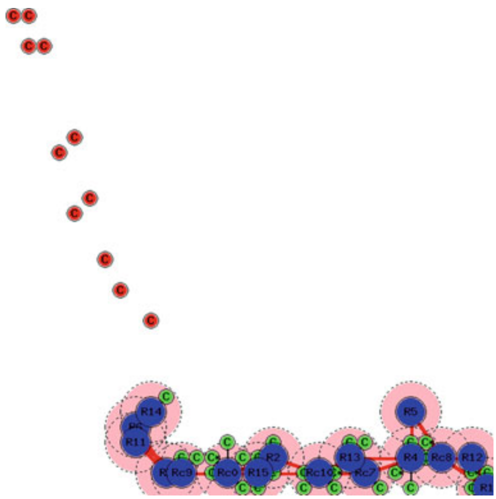
**Fig. 4** Simulation results for exponential distribution




(a) Size of Giant Component

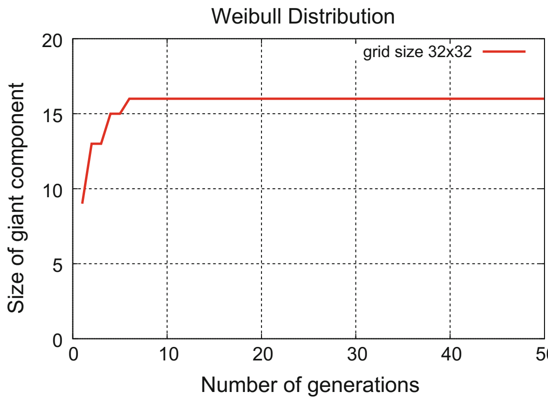



(b) Number of covered mesh clients

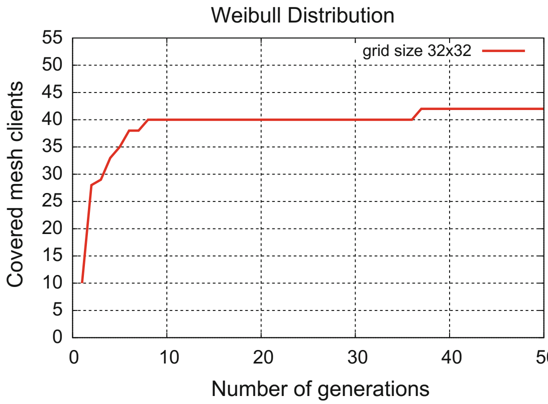


(c) Visualization

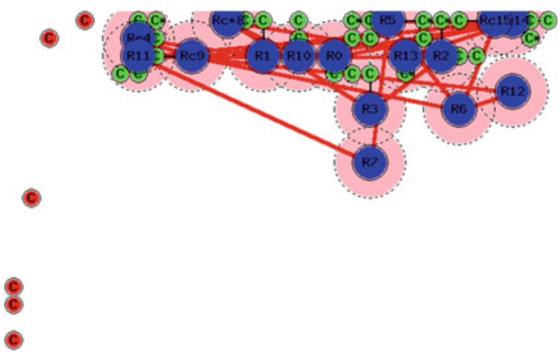
**Fig. 5** Simulation results for Weibull distribution




(a) Size of Giant Component




(b) Number of covered mesh clients




(c) Visualization

From the computational results we can see the performance of HC for different distributions of client mesh nodes. Best performance was achieved for instances with Normal distributions of clients. In particular, we can observe that the uniform distribution causes premature convergence. Finally, it's worth observing that the results corresponding to the Weibull and Exponential distributions are rather similar, which is reasonable since Weibull generalizes the Exponential distribution.

## 7 Conclusions

This work reveals and stresses the need to consider a plethora of resolution methods, such as exact methods, local search methods and population-based methods, to take advantage of their distinguished features such as exploitation versus exploration of solution space to efficiently solve the optimization problems in WMNs.

In this work we present some optimization problems in WMNs and HC algorithm for solving the problem of mesh router nodes placement in Wireless Mesh Networks (WMNs). In this problem, we are given a number of client mesh nodes a priori distributed in a grid area and a given number of mesh router nodes are to be deployed in the grid area. We formulate the problem as bi-objective optimization problem consisting in the maximization of the size of the giant component in the mesh routers network (for measuring network connectivity) and that of user coverage. We have also presented some experimental results from the HC method using a WMN simulator for small grid area size using different distributions of mesh node clients (Uniform, Normal, Exponential and Weibull). The main challenge identified here is the multi-objective nature of the node placement problems in WMNs. So far, only single optimization versions have been considered for the problem. We have considered the bi-objective case, and plan to extend the model to integrate more objectives resulting in a multi-objective optimization model where different objectives could as well be contradicting ones.

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