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Simulated Annealing in Telecommunication Network Planning

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Abstract: Fixed Wireless Access (FWA) systems overall design procedure is time consuming and critical for their successful commercial deployment as well as their efficient operation and management. The problem addressed in this research article is to find a model that can locate base stations in geographical layout area of 20×20 km^2 and connect end-users to the base stations. This research describes the mathematical model for the base station location problem in FWA-networks and solves the problem using Simulated Annealing while minimizing the number of not connected end-users within the given timeframe. The simulated annealing is implemented using C-programming language and the visualization of the results by the functions developed, using Matlab.

Key words: Fixed access wireless network, optimization, planning, simulated annealing

INTRODUCTION

Fixed radio technologies traditionally play an important role in telecommunication networks, especially if the right constraints, adverse terrain conditions and speed of deployment are the driving forces. Nowadays, Fixed Wireless Access (FWA) systems have been expected to contribute successfully to the provision of broadband internet services for telecommunication industry (Louta *et al*., 2003). With the liberalization and deregulation of the telecommunication sector in Ghana, FWA systems offer new operators unlimited access to a customer database, which has been fully in the hand of the fixed wired systems (Bölcskei *et al*., 2001)? From the user's perspective, the success of these systems will depend on the service spectrum they offer, as well as the quality of service they provide and especially, on whether it will be comparable to the quality levels offered by fixed wired systems. From the providers' view point, the aim will be to provide quality service in the most cost efficient manner. In this context, planning tools are expected to play a significant role in meeting these challenges, enabling operators to design from scratch or to expand and modify their systems by providing solutions to difficult combinatorial problems (Cheung *et al*., 1994).

Fixed Wireless Access is a variant of wireless broadband, where a radio link is used instead of a cable or fibre for the transmission of video, voice and data. Fixed wireless Access can be used for rapid internet access and video conferences especially in metropolitan areas. The communication goes from a transmitter to a fixed terminal fitted on a building roof, in contrast to mobile telephony where the communication goes from a transmitter to mobile terminals (Trinkwon, 2005). FWA provides a fast establishment and/or expansion of the connection between operator and end-user (Niels, 2000).

In the context of the overall planning for FWA, a number of problems may be addressed. The first aims at finding the minimum number of base stations, which guarantees sufficient radio coverage and traffic performance over a service area, thus providing the required quality of service, given the layout of the geographical area to be covered. The second is targeted to the efficient utilization of the (scarcely) available radio spectrum. The final stage is connecting the end-users to the base stations in the given geographical layout. In general, the task involves definition of the objective functions and specification of the respective problem constraints (related primarily to system performance requirements and equipment capabilities).

In this research article, we shall address two of the above problems. Location of base stations and the connection of end-users to the base stations. This research considers the planning of networks starting at a level where location and demand of each end-user and location of potential base station sites within the service area are known. Today, the radio network planning is done manually. Depending on the size of the desired network the process takes between three to five days for one person. This gives rise to promote the use of computers and operations research techniques to speed-up this process. The FWA system applied in this research article

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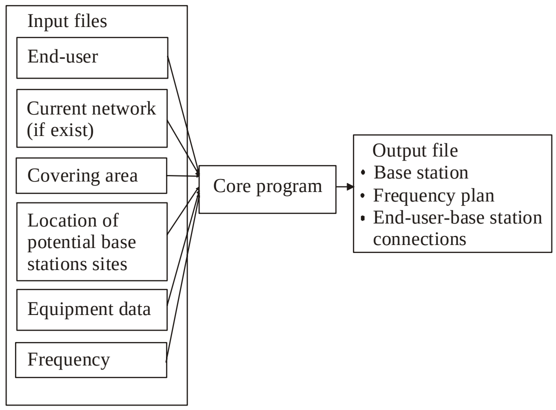

Fig. 1: Planning process for base station location

is the Vodafone MINI-LINK Broadband Access System (MINI-LINK BAS). The MINI-LINK BAS system provides connection between IP/PSTN/ATM backbone network and the end-user service terminals. The backbone network is connected to the base stations and one base station can be connected to a number of end-users (Point to Multipoint access (PMP)). One base station can host up to six sectors and each sector has a capacity of 37 Mbps Gross bit rate full duplex. One sector covers the end-users in an area within an angle of 90^0 with a maximum transmission range of approximately 5 km. This means that a base station with 4 sectors have a total potential coverage area that can be approximated by a circle with centre at the base station and a maximum radius of five kilometers.

One of the major tasks in Broadband Fixed Wireless Access planning is identifying the best location of base stations. The primary cost of the network is the cost of establishing base stations. The object is to minimize the number of base stations while maintaining 'sufficient coverage'. 'Sufficient coverage' is a matter of definition similar to the success parameter. The operator decides whether the network requested has to cover all potential end-users, or that the success parameter of e.g. 80% capacity utilization for base stations is acceptable. There exists other ways of defining the best network for the actual operator but these two are the most common. In a typical real-life planning process the first question is the cost of covering all end-users with sufficient capacity. Second question is how many end-users are covered with a minimum number of base stations, and is this number of end-users above operator's minimum service limit. This means that it is desirable to design a planning model in a way where both planning with unlimited and fixed numbers of base stations are possible. Figure 1 depicts the planning process under consideration.

This research is related to pertinent previous work, since software tools for cellular or broadband system design is a topic that attracts attention of most researchers in the telecommunication network industry.

While most FWA systems use a cellular structure they are far from cellular in their operations and characteristics. At this point we shall present the main features of FWA systems, which differentiate the overall design procedure with respect to mobile communication systems. The focal points are the following. First, as a consequence of users' fixed locations, the initial deployment of FWA systems aims at covering areas with high demand for innovating and traffic consuming services. Accordingly, FWA systems have a modular structure and they are developed gradually and progressively following the market demand curve. However, this is not the case in mobile communication systems, which aims at an initial wide area coverage. Secondly, there is no requirement for hand over procedure between neighboring end-users terminals, since the users do not move while a connection is in use. Moreover, FWA systems use narrow-beam, high gain antennas for consumer units, thus a careful and precise pointing is required. Again, the usage of sectorized antennas at end-users terminals with the employment of different polarization schemes, lead to an increased capacity, which in conjunction with the static nature of the paths make quality of service calculations more predictable, which enables the FWA systems to meet the higher bandwidth requirements for business connections. Finally, the line-of-sight nature of FWA systems mandated by the usage of microwave frequencies means that adequate coverage (one of the major prerequisites for successful commercial deployment) is dependent on terrain features and environmental conditions. In this context, the cell overlapping notion constitutes a desirable feature of FWA systems, as it forms a means of reliable coverage provision over the service area.

MATHEMATICAL MODEL FOR FWA

Design space: Design space for a FWA network is the geographical area that is sought covered. In the model the area is represented as a 2-D coordinate system.

End-users: End-users are the final consumers in the network. Their demands are voice, video and data services. The traffic load for these services is dynamic and it is represented by the average traffic load and the peak traffic, both in bits/sec. The load is the expected load of the end-user at a given year. The location of the end-user is either a company or a private domicile. In the model, each end-user's address is converted into a coordinate set in the 2-D model design space. End-users are identified by the index *i* in the model.

Base station site: Potential base station sites are locations where it is possible to place a base station. These sites are indexed by *j* and *k* and represented by a geographical coordinate set. In the model these values are converted to a set of coordinates in the 2-D model design space. The capacity of each base station is measured in bits/sec.

Radio propagation: The attenuation of radio signals is the limiting factor when considering the possible distance between base station and end-user. The attenuation is dependent on factors like obstructing buildings, rain attenuation, etc. For FWA the requirement for connection between base station and end-user is Line of Sight, (LOS). The radio attenuation is measured in dB is assumed linear dependent of the Euclidean distance between base station and end-user. A potential connection between a base station and an end-user requires that the Euclidean distance is below maximum transmission distance due to signal attenuation and where LOS exists. The signal strength at the end-user is assumed to be the transmitted power minus an attenuation constant multiplied by the Euclidean distance between end-user and base station.

Interference: When the network consists of more than one base station using the same frequency or one of the two adjacent frequencies, there is interference. Interference is measured as the relationship between the carrier signal from the assigned base station and the sum of interfering signals from other base stations, C/I. The interference is only interesting at the points where end-users are located. In this model the C/I is computed as the ratio of the signal strength at each end-user from its assigned base station and by the sum of signal strengths at the end-user, from all the rest of the base stations. The signal strength at an end-user from a given base station is computed according to the model mentioned in the preceding section 'Radio propagation' likewise is the interfering signal strength computed.

Three parameters identify the value of the network design. These parameters are 'minimal load on base stations in the solution' named *L*, 'number of connected end-users' found as the sum of $c_{i,j}$-variables and 'number of active base stations' found as the sum of b_j-variables.

The overall model for finding the maximal minimal load is given in Model 1. Notice that *L* in this model is a variable.

Model 1:

$$Z = \text{Max}\ (L) \qquad (1)$$

Subject to:

$$\sum_i c_{i,j}, d_i \left(1 - b_j\right). M \geq L \qquad \forall \text{j i} \in \text{I}, , \text{j} \in \text{J} \qquad (2)$$

$$\sum_i c_{i,j}, d_j \leq CAP_{\lim} b_j \qquad \forall \text{j i} \in \text{I}, , \text{j} \in \text{J} \qquad (3)$$

$$\sum_j c_{i,j} = 1 \qquad \forall \text{j i} \in \text{I}, , \text{j} \in \text{J} \qquad (4)$$

$$c_{ij} \leq k_{ij} b_j \qquad \forall \text{i, j i} \in \text{I}, , \text{j} \in \text{J} \qquad (5)$$

$$\left[\sum_j s_{ij}\left(1 - c_{ij}\right).k_{ij}\right].C/I_{\lim} \leq \sum_j \left(s_{ij}.c_{ij}\right) \qquad \forall \text{j i} \in \text{I}, , \text{j} \in \text{J} \qquad (6)$$

$$\sum_j s_{ij}.c_{ij} \geq SIG_{\lim} \qquad \forall \text{j i} \in \text{I}, , \text{j} \in \text{J} \qquad (7)$$

$$b_j.k_{ij}.\left(p_j - dist_{ij}.Att\right) = s_{ij} \qquad \forall \text{j i} \in \text{I}, , \text{j} \in \text{J} \qquad (8)$$

b, c $\in$ {0, 1}; p $\in$ [0, p_{max}]; s $\in$ R; L $\in$ [0, CAP_{lim}]

Model 2:
The mathematical formulation of the minimum cost model is as follows:

$$Min\left[\sum_j \left(CAP_{\lim}.b_j - \sum_i c_{ij}.d_i\right) Q_L + \sum_j b_j.Q_{BS} + \sum_{i,j} c_{ij}.Q_{EU}\right]$$

w.r.t

$$\sum_i c_{i,j}, d_j \leq CAP_{\lim} b_j \qquad \forall \text{j i} \in \text{I}, , \text{j} \in \text{J} \qquad (3)$$

$$\sum_j c_{i,j} = 1 \qquad \forall \text{j i} \in \text{I}, , \text{j} \in \text{J} \qquad (4)$$

$$c_{ij} \leq k_{ij} b_j \qquad \forall \text{i, j i} \in \text{I}, , \text{j} \in \text{J} \qquad (5)$$

$$\left[\sum_j s_{ij}\left(1 - c_{ij}\right).k_{ij}\right].C/I_{\lim} \leq \sum_j \left(s_{ij}.c_{ij}\right) \qquad \forall \text{j i} \in \text{I}, , \text{j} \in \text{J} \qquad (6)$$

$$\sum_j s_{ij} . c_{ij} \geq SIG_{\lim} \qquad \forall j \; i \in I, , j \in J \qquad (7)$$

$$b_j . k_{ij} . \left(p_j - dist_{ij} . Att \right) = s_{ij} \quad \forall j \; i \in I, , j \in J \qquad (8)$$

b, c ∈ {0, 1}; L ∈ [0, $CAP_{\lim}$]

Objective functions: The exact mathematical formulations of the objective functions are as follows:

$$Z = Max (L)$$

This function maximizes the minimum load variable *L*. Hence, at least one constraint has to be added to the model that bounds either minimum number of end-users connected or minimum number of active base stations.

$$Z = Min \sum_j b_j \quad j \in J \qquad (9)$$

This function minimizes the number of active base stations. When using this function with a constraint for minimum number of end-users connected, the average load on base stations is maximized.

$$Z = Max \sum_j c_{ij} \qquad \forall \; i,j \; i \in I, , j \in J \qquad (10)$$

This function maximizes the number of end-users connected:

$$Z = Min \left[\sum_j \left(\left(CAP_{\lim} - \sum_i c_{ij} . d_i \right) . Q_L . b_j \right) + \sum_j b_j . Q_{BS} + \sum_{i,j} c_{ij} . Q_{ij} \right] \quad i \in I, , j \in J \qquad (11)$$

$$Z = Min \left[\sum_j \left(\left(CAP_{\lim} . b_j - \sum_i c_{ij} . d_i \right) . Q_L \right) + \sum_j b_j . Q_{BS} + \sum_{i,j} c_{ij} . Q_{ij} \right] \quad i \in I, , j \in J \qquad (12)$$

These functions minimize the total cost of the network system. In Eq. (11), the first component, the demand connected to a base station *j* is subtracted from the capacity CAP_{lim}. This non-utilized capacity is multiplied by a cost constant Q_L and the binary variable b_j that indicates whether a base station capacity is available or not. Unfortunately, this construction results in a multiplication of the variables c_{ij} and b_j, which makes the objective function non-linear. It is crucial to have the binary b_j variable present otherwise non-active base stations contribute in a negative way with the total capacity.

In the second component, establishing a base station, $b_j = 1$, is multiplied by a cost and summed over all base stations.

In the last component, the binary variable $c_{i,j}$, indicating if end-user *i* is connected to base station *j*, is multiplied with the negative cost of not connecting end-user *i*, summed over all combinations of *i* and base station *j*.

The advantage with this formulation is the flexibility of the objective function. Any variable in the model can be priced and added as a component in the objective function. The layout of the function in Eq. (11) and (12) are the suggestion on how to price less desired elements in the network.

Constraints:
Constraint (2) stipulates that the connections between an end-user *i* and base station site *j* multiplied by the demand at end-user *i* summed over end-users *i*, must be greater than or equal to the minimum load variable *L*. If base station *j* is inactive, $b_j = 0$. For validity in the second component of the constraint, a large number, M, is added to the zero demand. The model generates one equation for each base station site *j*. This constraint ensures that the sum of loads from all end-users connected to base station *j* is above or equal to the minimum limit *L* if a base station exist at site *j*.

Constraint (3) ensures that the connections between end-user *i* and base station site *j*, multiplied by the demand at end-user *i* summed over end-users *i*, must be less than or equal to $CAP_{\lim}$ multiplied by the base station site *j*. We generate an inequality for each base station site *j*. This ensures that the sum of loads from all end-users connected to base station *j* is below or equal to the capacity at base station *j*.

Constraint (4) guarantees that the connections between end-user *i* and base station site *j* summed over base station sites *j* must be equal to one. The model generates an equation for each end-user. When c_{ij} is binary, this ensures that each end-user is assigned to exactly one base station site. In a model that strives toward a solution without all end-users, the equation is changed to an inequality.

Constraint (5) states that the connection between end-user *i* and base station site *j* must be less than or equal to the product of the legal connection identifier k_{ij} between end-user *i* and base station site *j* and the active base station identifier b_j. The model generates an equation for each combination of *i* and *j*. The equation ensures that end-users get connected to active base stations using legal connections.

$$C/I_{\lim} \le \frac{s_{ij}.c_{ij}}{\left[\sum_j s_{ij}.\left(1-c_{ij}\right).k_{ij}\right]} \quad \forall j\ i \in I, , j \in J \qquad (6A)$$

$$\left[\sum_j s_{ij}.\left(1-c_{ij}\right).k_{ij}\right].C/I_{\lim} \le \sum_j \left(s_{ij}.c_{ij}\right) \quad \forall j\ i \in I, , j \in J \qquad (6B)$$

In Eq. (6A), the signal power at end-user *i* from base station site *j* assigned to the end-user divided by the sum of signal powers at end-user *i* from base station sites *j* not assigned to the end-user *i* must be greater than or equal to C/I_{lim}. However, equations containing divisions with variables are always non-linear. To avoid this, we multiply both sides of the inequality sign by the denominator. This has been done in Eq. (6B). The model generates an equation for each end-user. This ensures that carrier to interference ratio is greater than or equal to the threshold value. Due to the multiplication of the two variables c_{ij} and s_{ij}, use of this equation will make the model non-linear.

Constraint (7) stipulates that the signal strength at end-user *i* from its assigned base station *j* must be greater than or equal to the minimum signal strength limit. The model generates an inequality for each end-user i.

Equation (8) ensures that the output power at base station *j* minus the attenuation product must be greater than or equal to the signal strength from base station *j* at the end-user *i*. The attenuation product is assumed to be constant multiplied by the distance between base station *j* and end-user *i*. The signal strength is only computed at each end-user from active base stations, $b_j = 1$ and at legal connections, $k_{ij} = 1$. This equation sets the output power value for each base station measured in dBm.

$$\sum_{i,j} c_{ij} \ge c_{\min} \qquad \forall j\ i \in I, , j \in J \qquad (13)$$

Constraint (13) ensures that the sum of end-user-base station connections summed over end-users *i* and base stations *j* must be greater than or equal to the value C_{min}. This equation also generates a constraint containing all potential end-user-base station connections. This equation ensures that at least C_{min} end-users get connected to a base station.

Simulated annealing: The optimal formulation comprises many variables. The usual next step for solving such difficult problems is to devise computationally efficient algorithms that may provide good solutions in reasonable time. Classical methods in this respect are simulated annealing (Aarts and Korts, 1989), tabu search (Glover and Laguna, 1998), genetic algorithms (Tsenov, 2000), greedy algorithms, etc. Hybrid or user defined heuristic techniques may also be devised.

As already stated, in this sub-section we present an algorithm that follows the simulated annealing paradigm.

Simulated annealing is a descent-search algorithm. Initialize with a start solution and a start temperature. Find the objective value by evaluating the start solution. Then find a neighborhood solution and evaluate this solution and move to this solution with a probability. If the new objective value is better than the actual value, the probability is '1'. Otherwise the probability is found as a function of the difference between the actual objective value and the new objective value and the temperature. After a number of solutions the temperature is lowered hereby lowering the probability of going to a worse solution. When the heuristic reaches the stop criterion it terminates.

The pseudo code Simulated annealing is as follows:

- Set t = start temperature
- Find a start solution x
- Compute the objective value F(x)
- Set the global best solution F(x*) = F(x) and (x*) = (x)
- Until global stopping criterion is reached do
  - Until local stopping criterion is reached do
  - find a neighborhood solution (x′) and compute the objective value F(x′)
  - If F(x′) ≤ F(x)
  - set (x) = (x′)
  - Else F(x′) > F(x)
  - set p = random number ∈ [0; 1]
    - If exp ((F(x)-F(x′))/t) < p
    - set (x) = (x′)
    - If F(x′) < F(x*)
    - set (x*) = (x)
    - Reduce temperature t

EXPERIMENTAL RESULTS

This section provides indicative evidence on the performance of our proposed algorithms, by applying them to a set of experimental data. Each experiment may generally be described as follows.

The simulated annealing, used in finding the optimal location of the base stations was coded in C. Matlab was also used to visualize the results. The input data consists of a set of potential sites where base stations and end-users may be deployed, capacity of each base station, demand of each end-user, coverage area, and equipment data (transmission frequency, transmission power). In this section our attention is limited to urban areas. The geographical layout used in our experiments is 20×20 km^2 (Sunyani Metropolis) grid networks. The FWA systems is operating in the frequency band of 26 GHz and the traffic demand originating from the service area were randomly chosen among companies and household within the design space, with between 25 and 500 employees or inmates. For every 5 employees or inmates the company/household demands 64 kbps. The resulting maximum transmission or coverage range is 5 km.

RESULTS

Figure 2 depicts the result of the first test run with seven base stations plotted. The number of non-connected end-users in this solution is 272 and the minimal load on a base station is 64.512 kbps. A visual inspection of the result unveils that our solution is sufficiently good. This is due to the non violation of the two constraints, tapering and overlap.

A plot of the results of the test run in the case with 9 base stations can be seen in Fig. 3. Here the number of non-connected end-users is 198 and the minimal load on a base station is 40.832 kbps.

The solutions in both cases were found within 15 sec. Naturally there is no violation of either tapering or overlap in the solution. There are no base station end-user connections that cross each other. On the other hand, the number of non-connected end-users is a bit higher in the solution. We have developed a solution which is closer to real life situation. We also evaluated C/I ratio of each end user with respect to an antenna. The number of end-users that has a C/I ratio greater than 22 dB is 680 in the case with 7 base stations, and that of the 9 base stations is 693. These results are considered realistic by senior specialist, Kloch at L.M. Ericsson, Denmark.

CONCLUSION

The research work is actually a generalization of the attempt by the authors to define an appropriate approach for implementing simulated annealing in the telecommunications networks planning for fixed wireless access. The algorithm is able to perform the location of base stations and connecting end-users in less than 60 sec using the number of non-connected end-users as optimization parameter. The results show that such an approach leads to good results.

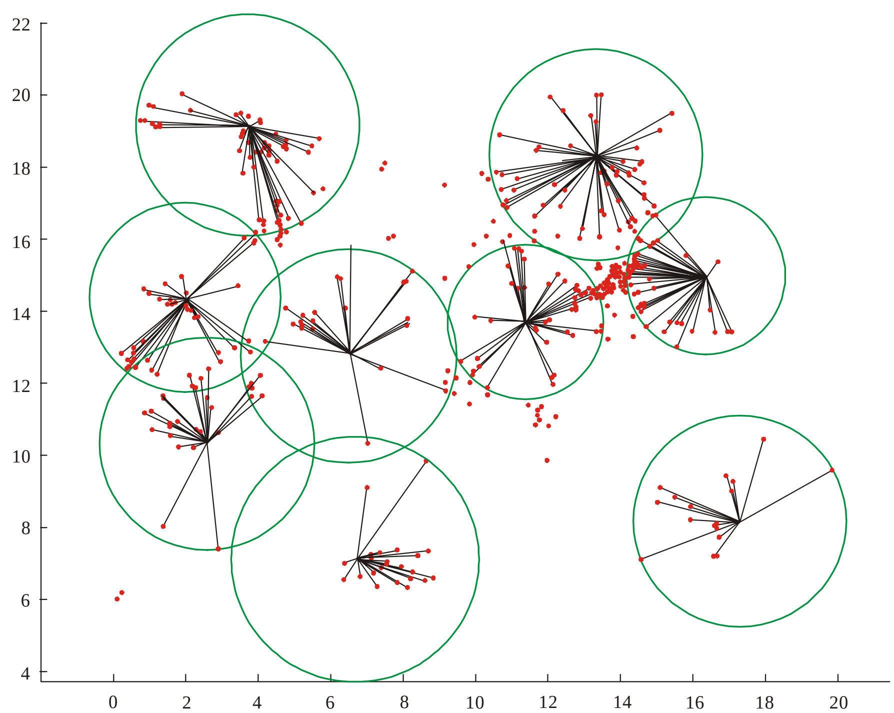

Fig. 2: Plot of first test run results

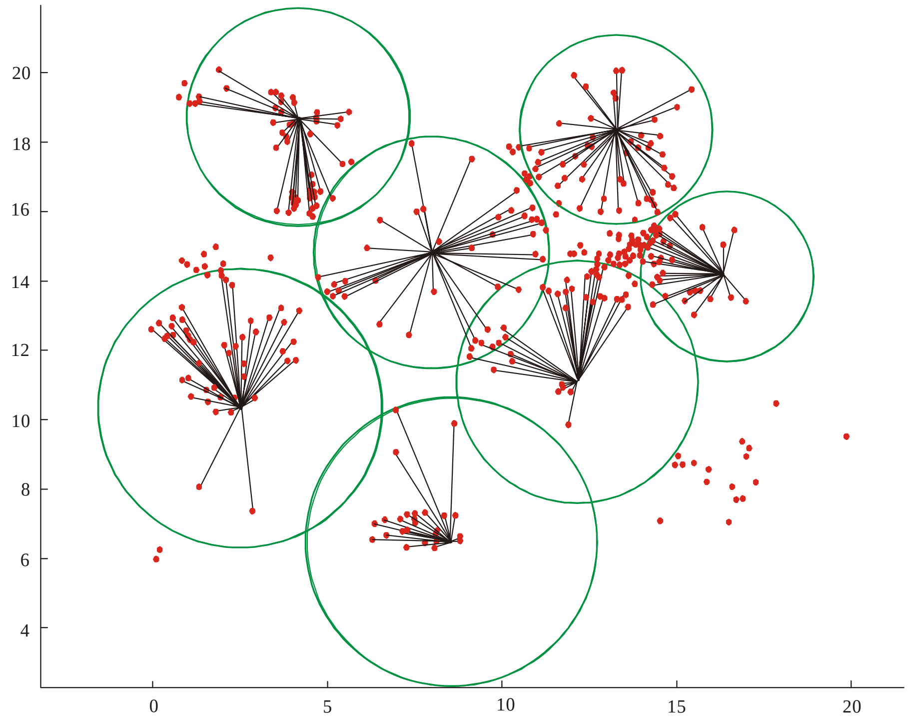

Fig. 3: Plot of second test run results

NOMENCLATURE

The variables in the model are as follows:

Factors	Symbol	Role	Range
End-user id	*i*	-	{1,2 … (I-1), I}
End-user coordinate	x_i, y_i	Structural factor	[0; X_{max} 0; Y_{max}]
End-user demand	d_i	Structural factor	[0; CAP_{lim}]
Base station site id	j, k	-	{1,2 … (J-1), J}
Base station coordinate	X_i, y_i	Structural factor	[0; X_{max} 0; Y_{max}]
Transmission power at base station	P_j	Decision factor	[0; P_{max}]
Base station at site	b_j	Decision factor	{0, 1}
Base station capacity	CAP_{lim}	Structural factor	R_+
Legal connections	k_{ij}	Structural factor	{0, 1}
End-user - base station connection	c_{ij}	Decision factor	{0, 1}
Minimum number of end-user base station connection	C_{min}	Decision factor	{0,1 … (I-1), I}
Signal at end-user from base station	s_{ij}	Conditional factor	[0; P_j]
Minimum C/I	C/I_{lim}	Structural factor	R
Minimum signal strength	SIG_{lim}	Structural factor	R
Load on base station	L	Conditional factor	[0; CAP]
Min. load on each base station	L_{lim}	Decision factor	[0; CAP]
Distance between end-user and base station	$Dist_{ij}$	Structural factor	R_+
Signal attenuation constant structural factor	Att.	Structural factor	R
Distance between two base stations j, k	$O_{j,k}$	Structural factor	R_+
Minimum distance between two base stations	O_{min}	Structural factor	R_+

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