COVERAGE ENSURING IN HETEROGENEOUS WIRELESS NETWORKS

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Wireless network cost-effectiveness always is of primary importance regardless of network type. One of the feasible solution lies on the way of heterogeneous networks, consisting of different kinds of nodes with various coverage abilities. The high-end nodes have greater servicing range; the low-end ones are much cheaper and with lesser service radius. A mixed deployment of these nodes can achieve a balance of coverage and cost of wireless network. In any case necessary coverage level at every point in the service area must be ensured. Some aspects of suitable network topologies for such kind networks are discussed. It is noted that in most cases network cost-effectiveness improvement with ensured 1-coverage is reachable, replacing particular low-end nodes by high-end ones at saving existing node allocation. Possible approach for near to optimal choice of candidates for such replacement is proposed. The approach is based on the mathematical apparatus of Voronoi tessellation, namely on multiplicative weighted Voronoi diagrams, allowing to take into account heterogeneity of the network. Proposed method allows finding a good approximation for optimal cost-effective heterogeneous wireless network topology saving the desirable level of network area coverage.

Keywords: *wireless networks, coverage, heterogeneity, homogeneity, Voronoi tessellations*

1. Introduction

The term wireless network (WN) refers to any type of network whose interconnections between nodes are implemented without the use of wires. There are lots of problems which define network performance and quality of service (QoS). One of the fundamental problems in wireless networks is coverage. Due to the large variety of wireless applications, interpretation of term "coverage" for different types of WN can vary, but in general, it answers the questions about the quality of service (QoS) that can be provided by a particular network. Simplistically coverage is a property of WN to deliver information to any point of serviced area, and may be defined as the probability that any target point in the serviced area is within the range of any nearby nodes.

Most known efforts in the area of wireless networks have focused on homogeneous WN (networks with identical nodes). As a rule, the area, covered by a node, is confined within a circular disk of radius R_s. On definition, covering disks of all nodes in a homogenous network have equal R_s. It is well known that the "best" way to cover a given area with circles of a given radius R, or to pack such circles within a given region is to place the centers of the circles on an equilateral triangle network, i.e. to circumscribe the circles about the hexagons of a regular hexagon network or honeycomb. However, regular network topology due to various reasons in practice is seldom. Generally desirable coverage in such WN can be reached by supplementing existing topology with additional nodes [1]. This way leads to substantial network redundancy, and therefore to its low cost-effectiveness.

The main question, examined in this work, is how we can improve the cost-effectiveness of WN, where the desirable level of network service area coverage is ensured at the expense of redundant nodes.

In general, two main approaches can be suggested for solution of this task: another deployment of existing nodes and replacement of particular low-end nodes with high end one. Both ways lead to appearance of nodes, useless for coverage insurance. These nodes are eliminated from the WN, thus the total cost of network falls.

The first approach can be applied for some sensor networks, but conformably to other types of WNs usually is inapplicable. We'll focus on the second approach, namely, enhancement of network cost-effectiveness by replacement of a few nodes of existing WN with more powerful ones. Wireless networks, consisting of nodes with different service radii, are known as heterogeneous wireless networks (HTWN).

Some problems of coverage in HTWN are examined in [2-6], however, questions of how many, and which low-end nodes to replace for getting the best network cost-effectiveness remain largely unexplored.

In this paper, we discuss possible 1-covered homogenous WN transformation way into cost-effective heterogeneous network with coverage preserving.

2. Coverage in Heterogenous Wireless Networks

In this section, the influence of low-end nodes replacing by high-end ones on the total network coverage probability is examined.

We first study the coverage problem in homogeneous networks for completeness, and then we analyze the coverage problem in the heterogeneous case with two types of nodes, but all said can be extended to wireless networks with more than two types of sensor nodes. Analysis is based in [5].

In homogenous WNs, all the nodes have the same service range R_s. Suppose that nodes are deployed randomly in a square area of size $A = L \times L$ with node density $\lambda = \frac{N}{A}$, where N is the total number of nodes. For simplification we assume a simple deterministic radio model, where target can be reached if it is located within the range of R_s [1].

We consider the case, where a target point in the network area is reputed as being covered when it is located within the service range of at least one WN node. This situation is defined as 1-coverage. The 1-coverage probability is the probability that there is at least one node located within the disk with radius R_s centered at a target point in the serviced area. For uniformly distributed WN with node density λ, the probability that there are m nodes within the area of S is Poisson distributed:

$$P(m) = \frac{(S\lambda)^m}{m!} e^{-S\lambda},$$

where $S = \pi R_s^2$.

The probability that the monitored area is 1-covered, denoted by $P_{cover\text{-}1}$, can be expressed as:

$$P_{cover-1} = 1 - e^{-S\lambda}.$$

Considering coverage for heterogeneous networks we focus on HTWNs with two types of nodes. We define the nodes with greater service range as type 1 (T1) nodes and the nodes with lower service range as type 2 (T2) nodes. We assume that the type 1 nodes' service range is R_{s1}, and that of type 2 nodes' is R_{s2} ($R_{s1} > R_{s2}$). The densities of T1 and T2 nodes are λ_1, and λ_2, respectively.

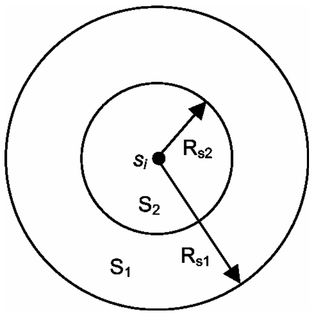


Figure 1. Coverage in heterogeneous case

To achieve 1-coverage in the heterogeneous network with two types of nodes, there must be at least one Type 1 node located within the area $S_1 = \pi R_{s1}^2$ or at least one Type 2 node located within the area $S_2 = \pi R_{s2}^2$ around each target point. As shown in Figure 1, for the arbitrary point s_i to be 1-covered, there must be at least one T2 node around s_i within S_2, or one T1 node around s_i within S_1.

The probability that there is no type 1 nodes around s_i within T1 nodes' service coverage area S_1 is $P_1 = e^{-S_1\lambda_1}$. Similarly, the probability that there are no type 2 nodes around s_i within T2 nodes' service coverage area is: $P_2 = e^{-S_2\lambda_2}$ .Thus, the probability that there is at least one node (either T1 or T2) that could monitor point s_i is 1 - P_1P_2. If $P_{cover-1}$ denotes the 1-coverage probability for a randomly chosen point, the probability that the point could be 1-covered can be expressed by the following equation:

$$P_{cover-1} = 1 - P_1 P_2.$$

Given the node density and the service range, the coverage probability of the total serviced area can be estimated.

Appropriate investigation [5] shows that coverage probability in the heterogeneous case increases substantially with an increase in T1 nodes than the homogeneous case. Thus in order to get the 1-coverage probability of 0.8 in homogenous case at $R_{s1} = 3R_{s2}$ we need to deploy about 120 type 2 nodes in addition to the original fixed 300 ones; while in heterogeneous case, we only need to deploy about 10 type 1 nodes to provide the same coverage probability.

So, as it follows from abovementioned, transformation of homogenous WN into heterogeneous one can be an effective way for achievement of desirable level of coverage. Such transformation can be also useful for homogeneous networks where 1-coverage already takes place. By replacement of some T2 nodes by T1 nodes and removing nodes, whose service disk now is fully covered by these T1 nodes, we can sufficiently raise common WN's cost-effectiveness, while preserving existing coverage level.

3. Conditions of Optimal Coverage

In this section the problem of wireless network optimal topology choice, suiting service area full coverage demands, come into question.

Previously it was marked that a point is considered as covered, if it is within the service area of at least one wireless network node. Node coverage area is represented by a disk with the radius R_s. Thus, network service zone coverage is reduced to the task, known from geometry, namely, given area coverage by overlapping disks. Simplistically, we can consider that the most cost-effective network be a network with minimal number of nodes.

As it is stated in [6], minimization of network node quantity, which ensure 1- coverage of given area *A*, may be reduced to minimization of total overlapping area of all network nodes. For determination of overlapping area minimization conditions we introduce the concept *of* Intersection Point. By this term we'll designate intersecting points of two node's service circles, or one circle and the boundary of the monitored region *A*. In Figure 2 intersection points are marked by crosses. It is assumed that disk size is smaller than that of the region *A*.

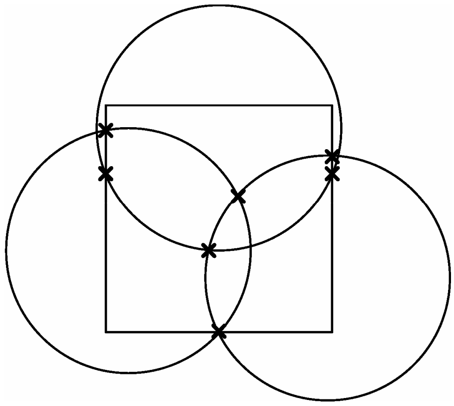


Figure 2. To the concept of Intersection Point

Service area *A* is 1-covered, if the followings essential conditions are satisfied [6]:

- crossings exist;
- every crossing between two disks in the monitored region is an internal point of a third disk within the network service area;
- every crossing between the disk and the boundary of monitored region is an internal point of the third disk within the service network service area.

Minimization of total number of nodes, fully coverings area *A*,, reduces to minimization of total overlapping area of all network nodes. For homogeneous network in order to minimize overlap when covering a crossing point, three nodes (figure 3) need to be placed such that

$$s_1 s_2 = s_2 s_3 = s_1 s_3 = \sqrt{3} R_s ,$$

where *Rs* is the service range of a node.

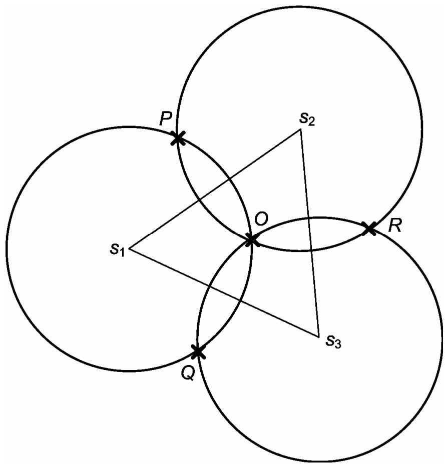


Figure 3. Optimal overlapping of three disks in a homogeneous network

If the positions of two nodes are fixed, then the third node should have equal distance to the other two nodes and its disk boundary (circle) should just cross the crossing point *O*.

In the case of heterogeneous network (Figure 4), when the radii of all disks are different, in order for minimizing overlap, three nodes need to be placed such that $OP = OR = OQ$.

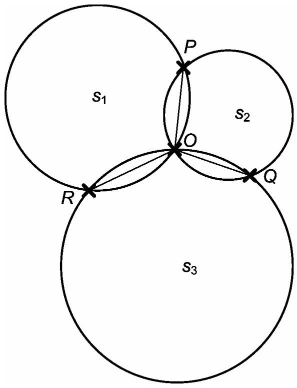


Figure 4. Optimal overlapping of three disks is in a heterogeneous network

If the positions of two nodes s_1 and s_2 are fixed, then the third node s_3 should be placed such that $OQ = OR$.

For creation of homogeneous network the OGDC (Optimal Geographical Density Control).algorithm usually is used. The essence of this algorithm can be reduced to the followings positions:

1. Create some crossing.
2. Cover the crossing using a new node that incurs minimal overlap.
3. Repeatedly cover the new generated crossing until no uncovered crossing exists in the given region *A*.

Unfortunately, this method is inapplicable to the heterogeneous networks, as does not answer the question about what type of node it is expedient to add at next iteration.

4. Creating of Cost-Effective Heterogenous WN

Most of wireless networks usually are homogeneous. The optimal decision for 1-coverage in such WNs is the symmetric allocation of nodes, where they form a hexagonal grid. Unfortunately, symmetric arrangement of WN nodes in the real life is uncommon. More typical are networks with the arbitrary allocation of nodes, at that some regions in the WN's service area can appear uncovered. At lump of nodes, as, for example, in sensor networks, coverage can be attained by changing the placement of existing nodes. For other types of wireless networks displacement of already allocated nodes is usually inadmissible, and blanks in coverage are abolished by adding extra nodes. There are known different algorithms for coverage ensuring by adding subsidiary nodes [1], but in all cases it leads to large superfluity of network. Intuitionally it is possible to notice on the example of network, considered in [1] and resulted in a Figure 8a, where for 1-coverage of a square region 1 × 1 with disks of radius R_s = 0.1 about 76 nodes are need.

Superfluity in number of nodes leads to WN's cost-effectiveness fall. The situation can be improved if at the disposal of the user there are nodes with different service radii, for example, before mentioned nodes of type 1 and type 2. Then the total amount of nodes in a network can be reduced by replacing certain T2 nodes by nodes of type 1 with greater service radius. The network becomes heterogeneous. Remaining T2 nodes, whose service disk is fully covered by service disks of installed T1 nodes, become unnecessary and can be moved away from the WN. The process of such replacements can be taken to the stage, when 1-coverage is provided only by nodes of type 1 and the final network topology again becomes homogeneous. From the positions of WN's cost-effectiveness the latter it is not always profitable.

In transition to the heterogeneous network naturally arises a problem of optimal choice of commutable nodes. In the strict sense optimal will be decision at which minimal will be the total cost of all network nodes.

This sort of tasks is well studied. It is known that getting a strict optimal decision is difficult or sometimes impossible. On this account instead of optimal decision some kind of approximation is usually searched.

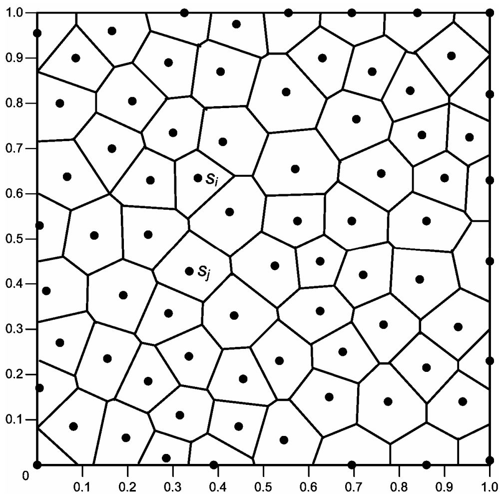
In this work we suggest a method for converting 1-covered WN with surplus nodes into heterogeneous network, having near to optimal cost effectiveness. The method is based on the mathematical apparatus of Voronoi tessellations, as well as on the algorithm of redundant node recognition, resulted in [6].

4.1. Mathematical Framework

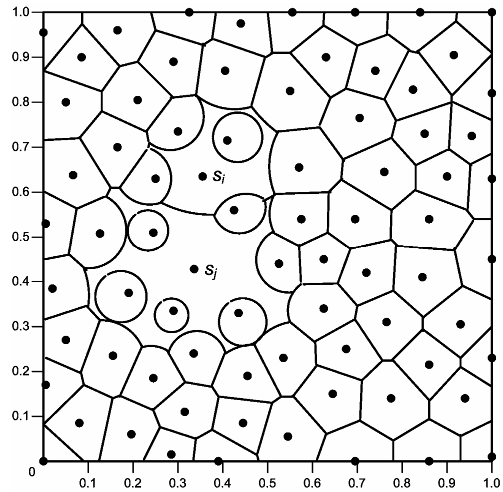
A classic way of node regionalizing or allocating space around a predetermined set of points or nodes is Voronoi tessellations. In respect to problem under discussion three kinds of Voronoi tessellations are to be mentioned: Voronoi diagram (VD), multiplicatively weighted Voronoi diagram (MWVD), and 2-Voronoi diagram (2-VD).

The 2D Voronoi diagram of a set of discrete sites (nodes) s_1, s_2, ..,s_n partitions the plane into a set of convex polygons or cells such that any point in the cell corresponding to a site is closer to that site than to any other site. Formally, the Voronoi cell corresponding to site s_i is defined as

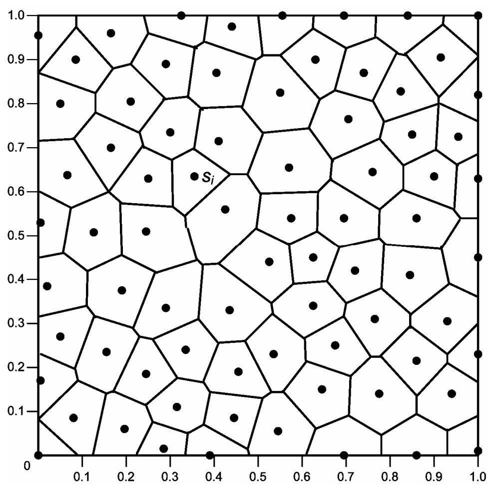
$$c_{vd}(s_i) = \bigcap_{j=1, j \neq i}^{n} \{x \mid d(s_i, x) \leq d(s_j, x)\}.$$



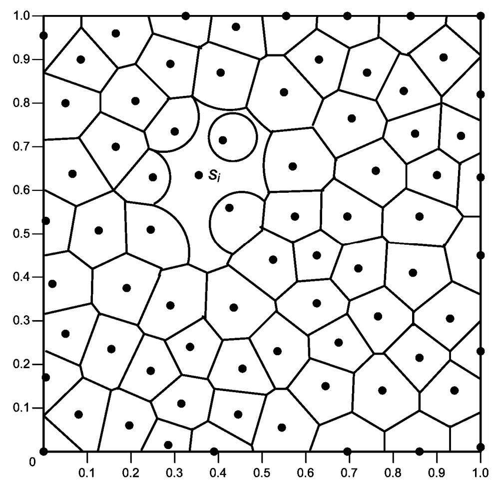
Voronoi diagram



Multiplicative weighted Voronoi diagram



2-Voronoi diagram



Multiplicative weighted 2-Voronoi diagram

Figure 5. Examples of different kind Voronoi diagrams

This construction effectively produces polygons with edges that are equidistant from neighboring sites. We use the notation $d(p,q)$ to denote the Euclidean distance between two points p and q. Two Voronoi cells meet along a Voronoi Edge, and three Voronoi cells meet at Voronoi Vertex. We call a site a neighbor of another site if the Voronoi cells of the two sites share an edge.

Multiplicative weighted Voronoi diagram is defined in a manner similar to a Voronoi diagram, with the addition of weight at each site

$$c_{mwvd}(s_i) = \bigcap_{j=1, j \neq i}^{n} \{x \mid d_{mwvd}(s_i, x) \leq d_{mwvd}(s_j, x)\}$$

where $d_{mwvd}(s_i, x) = \dfrac{d(s_i, x)}{w_i}$.

A Voronoi diagram is, thus, a method for dividing an area into regions or polygons so that all locations enclosed within a single polygon are closest to a designated point. A weighted Voronoi polygon can be utilized when nodes differ in service range to draw polygons around them accordingly. Thus more powerful nodes will have larger polygons drawn while nodes with fewer R_s have smaller ones based on the distances between the nodes.

The construction of weighted Voronoi diagrams is computationally more difficult than the Voronoi diagrams. Instead, specialist packages such as GAMBINI are available to complete the task.

The 2-Voronoi diagram of a node is the Voronoi diagram of the Voronoi neighbors of s_i when s_i is excluded. The 2-Voronoi Vertices (2-VV) of a node s_i are the Voronoi vertices of the 2-Voronoi diagram of s_i. A 2-Voronoi Intersection Point (2-VIP) of a node s_i is the intersection between an edge of the 2-Voronoi diagram and the coverage circumcircle of s_i. A 2-Voronoi Edge (2-VE) of s_i is either a Voronoi edge between 2-VIV's of s_i or a Voronoi edge between a 2-VV and a 2-VIP of the 2-Voronoi diagram of s_i.

For heterogeneous networks 2-Voronoi diagram must be replaced by multiplicative weighted 2-Voronoi Diagram (2-MWVD), which can be defined in similar manner by replacing the ordinary VD by appropriate MWVD.

Figure 5 illustrates examples of different Voronoi tessellations.

4.2. Offered Algorithm

In this section we propose an algorithm for 1-covered wireless network optimization by replacing the nodes, having lesser service radius by the nodes, possessing larger radius at coverage preserving. The method is examined for the case of two types of nodes: T1 and T2.

As a start position is taken a wireless network, mainly or fully consisting of T2 nodes, but with a condition that it is already 1-covered. Network transformation procedure comes to the end when the criterion function WN_{cost} reaches its minimal value. The criterion function WN_{cost} reflects the cost-efficiency of network and can be defined as

$$WN_{\cos t} = N_H \times k_{\cos t} + N_L ,$$

where N_H and N_L are amounts of T1 and T2 type nodes accordingly, k_{cost} is a ratio of T1 and T2 node cost.

The offered algorithm can be described as follows. Nodes of T2 type by turns are substituted by the T1 nodes. At each replacement, all the rest T2 nodes, whose service disks are fully covered by service disk of new T1 nodes, become surplus.

At first stage of the examined algorithm each of type 2 node in turn is replaced by T1 node. Ordinal number of replaced node as well as the quantity of surplus T2 nodes, arising after the replacement, is fixed. On the results of the first stage the node, whose replacement creates the greatest number of surplus nodes, is defined. For this node is calculated and fixed the value of criterion function. Next, the T1 node constantly replaces the appropriate T2 node, but all surplus nodes are retired from the network. Similar actions repeat for new network configuration, but during all subsequent iterations the calculated value of WN_{cost} function is compared with its value, fixed at previous iterations. If new value of criterion function is less, then modification of network is made and next iteration start. Otherwise the last modification of the network is not made and the process of optimization goes to the end.

The described procedure itself is enough trivial. A basic problem is to make sure that a node is redundant. In the examined method this problem is solved by using 2-VD diagrams. As it is proved in [6], in a homogeneous network node s_i is surplus, if all the 2-VVs and all 2-VIPs of s_i are covered by the Voronoi neighbors of s_i. An example of redundant node s_1 is shown in Figure 6.

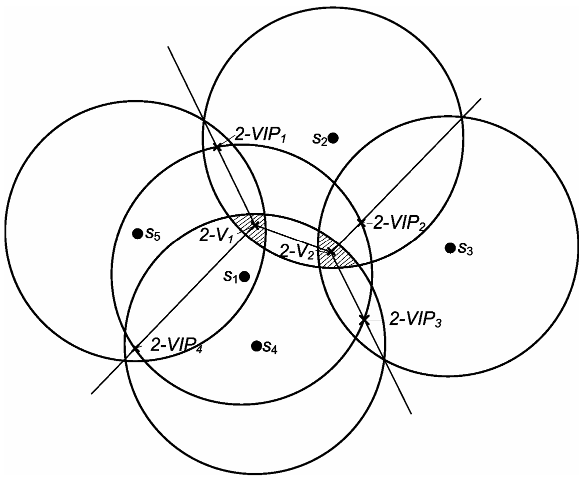


Figure 6. Detection of redundant node s_1

In the figure points 2-V_1 and 2-V_2 are 2-*VV*s of s_1, and 2-$VIP_{1...4}$ are 2-Voronoi intersection points of s_1. Note that 2-$V_{1,2}$ and 2-$VIP_{1...4}$ are all covered by at least two of Voronoi neighbors of s_1.

Substantially, that the indicated position statement remains also for a heterogeneous network at the replacement of 2-VD by 2-MWVD, that allows to use it in the examined algorithm.

Summarizing, we can describe the algorithm in such steps:

Step 1 For the initial network configuration calculate and fix the value of *WNcost* function.

Step 2 Replace one of the type 2 nodes by a node of type 1. For the modified network build a 2-MWVD diagram, and on its basis reveal surplus nodes of type 2. Fix numbers of these nodes and their quantity. Restore network configuration to its state at the beginning of step 1. Repeat abovementioned actions for each T2 node.

Step 3 On the basis of the second step select a node, whose replacement leads to the greatest number of surplus nodes of type 2.

Step 4 For configuration with replaced node, defined on step 3, calculate the value of WN_{cost} function and compare it with its previous value. If it is not less than previous, complete the procedure.

Step 5 Replace the node, chosen on the step 3, by a T1 node, and remove from the network surplus nodes of type 2.

Step 6 Return to the point 1 using as initial network configuration got in item 5.

Modeling of described algorithm showed that final network configuration may be sufficiently near to the optimal one, at that approximation degree grows with increasing $\frac{R_{s1}}{R_{s2}}$ ratio. The latter can be explained by that at small distinction of R_{s1} and R_{s2} many of T2 nodes get covered only partly. This failing can be overcame due to some complication of the procedure, namely by simultaneous replacement of not even nodes, but pair of neighboring nodes.

Surplus nodes on every step may be also recognized visually (figure 7), but at plenty of nodes this choice becomes too laborious.

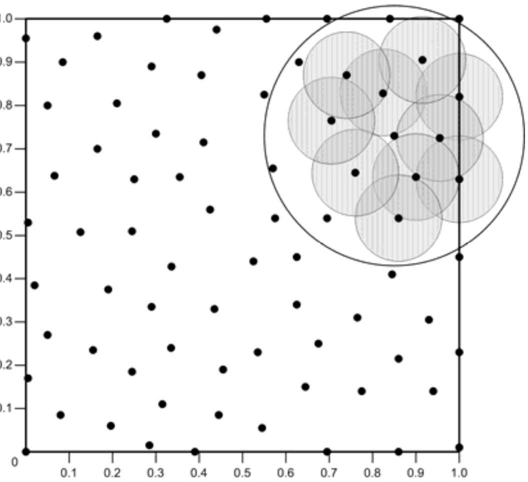
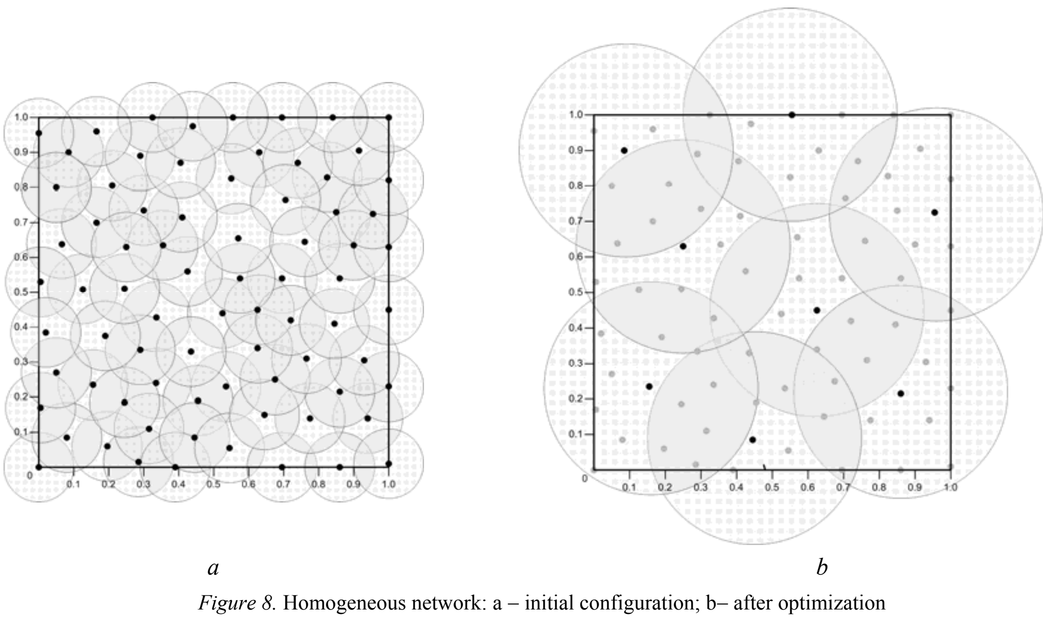


Figure 7. Visual determination of surplus nodes

We'll mark that the result of the described algorithm not necessarily leads to a heterogeneous network. In the extreme case it can be a homogeneous network, but already consisting T1 nodes, Example of such case, for initial network, taken from [1] and resulted in Figure 8a, at $R_{s1} = 3R_{s2}$ is shown in Figure 8b.



a *b*

Figure 8. Homogeneous network: a – initial configuration; b– after optimization

Conclusion

An algorithm for wireless network cost-effectiveness rise with coverage preserved by replacing separate network nodes with nodes, having greater service radius, i.e. by passing to heterogeneous network is offered. At mentioned replacements some of initial nodes with smaller service radius become unnecessary for ensuring the network's area coverage and are eliminated. Methods for detecting redundant nodes arising due the replacement are suggested.

The proposed algorithms give a practical way for increasing cost-effectiveness of existing wireless networks.

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