Centre of Mass of single coverage: A comparative study with Simulated Annealing for mesh router placement in rural regions

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RÉSUMÉ. Ce travail s'attaque à un problème critique dans la planification de réseaux maillés sans-fil pour zones rurales : le placement de nœuds maillés. Le but est de maximiser la couverture tout en réduisant autant que possible le nombre de nœud dans le réseau et en assurant la connectivité. Pour atteindre cet objectif, nous proposons une approche basée sur le calcul du barycentre de la zone couverte par un seul routeur. Cette approche est dix fois plus rapide que l'approche basée sur le recuit simulé. En outre, les simulations ont aussi montré une faible variation des solutions, traduisant ainsi une certaine stabilité de l'approche. Toutefois, la qualité des solutions obtenues en termes de couverture des zones d'intérêt avec le recuit simulé reste meilleure.

ABSTRACT. This paper tackles a critical issue in the planning of rural wireless mesh network (RWMN): the mesh node placement. The aim in the planning of RWMN is to maximise the coverage while keeping the number of router as few as possible and ensuring the connectivity. To achieve this, we proposed an approach based on the calculation of the centre of mass of areas covered per router. This approach is ten times more time-efficient than the simulated annealing one. In addition, the simulations results also provide a low variation of the solutions, showing some stability of the approach. However, the quality of the solution in terms of coverage of areas of interest provided by the approach based on Simulated Annealing is better.

MOTS-CLÉS : Centre de Masse, Recuit Simulé, Réseaux maillés sans fil, Placement de router maillé.

KEYWORDS: Centre of mass, Simulated Annealing, Wireless Mesh Networks, Mesh router placement.

1. Introduction

A Wireless Mesh Network (WMN) [1] is a wireless network in which nodes are connected in a mesh topology. This kind of network is an appealing cost-effective solution to bridge the digital divide observed between rural and urban regions, since it is based on off-the-shelf material especially WiFi technology.

Rural Wireless Mesh Networks (RWMN) are usually composed of one gateway which connects the network to Internet, and a set of mesh routers (MRs). The success of the planning of such networks depends on the determination of an optimal number and placement of its mesh nodes. The planning of wireless networks in rural regions is more coverage-driven than capacity-driven [2], with the aim of minimizing the overall cost of the architecture, while maximizing the coverage percentage of the area to cover.

For realistic deployment scenarios, the problem of mesh node placement is a NP-hard combinatorial optimization problem which cannot be solved in polynomial time [9], [10]. This is why metaheuristics are usually required to optimize the planning.

This paper considers the network model found in [3]. In this model, a given area to cover is decomposed into elementary areas which can be required or optional in terms of coverage and where a node can be placed or not. An extension is made to this model in order to consider the presence of obstacles that can hinder the connectivity. The aim is therefore to determine the location of mesh routers which maximizes the coverage of area of interest. To achieve this goal, a placement approach based on the calculation of the centre of mass (CM) of area covered per router is proposed. This approach is compared to the simulated annealing (SA) approach defined in [4] to solve the same problem.

The rest of the paper is organized as follows: Section 2 briefly presents related work in WMN planning. Section 3 defines the network model and formulates the placement problem. Section 4 explains the approach based on the calculation of the centre of mass of area covered alone by a router. Section 5 presents the experimental setup and discusses the results in comparison with simulated annealing ones. This paper ends with a conclusion and future work.

2. Related Work

The work in [5] provides a good overview of the planning problem in WMN. This survey classifies the planning problem according to the flexibility of the network topology: unfixed (not-predefined) and fixed (predefined). In fixed topology, all the nodes in the network have a predefined location. The problem is therefore more related to routing protocols, channel assignment, or joint approaches. In unfixed topology, the location of at least some nodes is not predefined in the network: either the gateway(s) or the mesh routers, or both. This problem is usually assimilated to the one of facilities and locations with mesh routers representing facilities and the users to serve representing locations.

To solve the placement approach, different formulations have been proposed in the literature. They depend on the type of node considered in the planning problem: mesh routers [6], gateways(s) [7], or both [8]. Linear programming based approaches [9] have been used; but since this problem is known to be hard for real size deployment [9], search techniques and meta-heuristic are usually used [6, 10, 11, 12]. The region to be covered, usually called the universe, can be considered as continuous (a whole region), discrete (a set of predefined positions) or network (undirected weighted graph).

In [10], an approach based on simulated annealing has been proposed to solve the mesh nodes placement problem. It aims to find optimal locations of routers that maximize the network connectivity and client coverage, given a two-dimensional area with a number of fixed client nodes.

The work in [13] introduces the placement problem of mesh routers in a rural region. It has been extended later in [3], wherein a region is considered as decomposed into a set of elementary areas which may require the coverage or where a node may be placed. A placement approach based on metropolis algorithm has been therefore used.

3. Formulation of the Placement Problem

A given region is composed of areas of interest that should be covered as it is in [4]. The coverage of a region is considered as optional when this region is not of interest. A given region comprised also prohibited areas where a node cannot be placed (lake, river, road…), and a set of obstacles that could hinder the connectivity.

The area to cover is modelled as a two-dimensional irregular form in a two-dimension coordinate plane. We consider the smallest rectangle that can contain the irregular form. Therefore, we assume that this rectangle is decomposed into small square forms. Each discrete point is called elementary area (EA), which can be of one or more types: Elementary Area of Interest (EAI); Non-line-of-sight Elementary Area (NEA); or Prohibitive Elementary Area (PEA).

We define a set of two-dimensional matrices in order to characterise each EA: *Cover* indicating whether an EA requires coverage; *Place* indicating whether we can place a node in an EA; *CoverDepth* indicating the number of routers covering an EA; and *Pathloss* indicating whether an EA contains an obstacle. Therefore, an EA at position (x, y) can be characterised by (1-4).

$$\mathrm{Cover}(x, y) = \begin{cases} 0 \rightarrow \text{coverage not required} \\ 1 \rightarrow \text{coverage required} \end{cases} \quad \textbf{(1)}$$

$$\mathrm{Place}(x, y) = \begin{cases} 0 \rightarrow \text{cannot place a node} \\ 1 \rightarrow \text{can place a node} \end{cases} \quad \textbf{(2)}$$

$$\mathrm{CoverDepth}(x, y) = \begin{cases} 0 \rightarrow \text{no coverage} \\ n \rightarrow \text{covered by n routers} \end{cases} \quad \textbf{(3)}$$

$$\mathrm{Pathloss}(x, y) = \begin{cases} 0 \rightarrow \text{no obstruction} \\ p \rightarrow \text{attenuation factor} = p \end{cases} \quad \textbf{(4)}$$

To simplify the problem, we assume that the attenuation factor of any obstacle in the line of sight between two routers is high enough to prevent any wireless link between those routers. We also assume that all routers are equipped with an omnidirectional antenna all having the same coverage radius (r). The radius is expressed as the number of EAs (r = 6 means that the radius stretches over 6 EAs).

Let p be an EA at position (x, y). If a mesh node is located in p, then the set of EAs covered by this mesh node is given by (5).

$$\forall (a, b), (x - a)^2 + (y - b)^2 < r^2 \quad \textbf{(5)}$$

The population is not so dense in rural regions when comparing to urban ones; thus, we consider as in [2] that the planning is coverage-driven, meaning we are more concern by the space to cover than the throughput to deliver. The mesh router placement problem in rural regions can be therefore described as the determination of a minimum set of positions, which maximizes the coverage of areas of interest, while minimising the cost of the architecture and ensuring the connectivity. This cost can be minimised just by minimising the number of routers required to cover the region.

4. Centre of mass of single coverage

4.1. Algorithm

The idea behind the approach of the centre of mass of single coverage is to reduce the area covered by multiple routers by drawing routers to the centre of mass of area they are covering alone. This approach is motivated by the fact that by moving routers to the centre of mass of their single coverage, new non-covered EAI can be reached in a relative short number of moves compared to the number of moves required by the SA approach. In fact, in the SA approach, the location where to move a selected router is chosen randomly while ensuring that $Cover$ = 1, and $Place$ = 1. The SA approach is given in Appendix 1.

Algorithm 1: Centre of mass of single coverage

Input: f : the objective function to be maximized

Output: s: the best solution found

```
Begin
    s:= InitialSolution();
    v:= f(s);
    while (stopping condition not met) do
        i:=selectARouter();
        if multiple coverage ofi is too large a fraction then
            Search for an EA with CoverDepth = 0, Cover = 1, and Place = 1
        else
            Move i to the centre of mass of his single coverage
        s := NewSolution(i);
        v := f(s)
    returns
End
```

4.2. Algorithm explanation

Initial Solution: The initial solution is obtained by placing routers randomly in the area to cover while ensuring that $Cover$ = 1, and $Place$ = 1. For each router we randomly select an EA until Cover(EA)=1 and Place(EA)=1be satisfied. We therefore place the current router in this EA. A minimal number of routers for covering a given region can be determined by (6). But this minimal number is not enough to cover the region since routers should overlap to ensure the connectivity, and the form of the region is irregular. We use an initial number of routers 1.5*nr_{min}.

$$nr_{min} = \left\lceil \sum \mathrm{Cover}(x, y) \ /(r^2 * 3.14) \right\rceil \quad \textbf{(6)}$$

Single and multiple coverage: Let us consider $sCov(i)$ and $mCov(i)$ to be respectively the single coverage and the multiple coverage of router$i$. To check whether multiple coverage is too large a fraction, we use the expression in (7). In this expression, $rand(x)$ is used to provide some probability. We can remark that when $sCov(i)$is too great compared to $mCov(i)$, expression in (7) has a great probability to be not satisfied. If it is the case, the router is moved to the centre of mass of its single coverage; reducing eventually its multiple coverage. Otherwise it is relocated to another EA selected randomly. However, the EA should be one that requires coverage, which is not yet covered, and where a node can be placed.

$$\left(sCov(i) + mCov(i)\right)^2 * rand(\mathrm{x}) < (mCov(i))^2 \quad \textbf{(7)}$$

Fitness function (lines 3 and 11): The evaluation of fitness function consists to count the number of covered EAI. This is done by (8) after the initialisation. Because we move only one router at the same time, we consider only the EAs of this router which are concerned by the move.

$$\mathrm{f} = \sum \mathrm{sign}(\mathrm{CoverDepth} .* \mathrm{Cover}) \quad \textbf{(8)}$$

New Solution (line 10)**:** It is obtained by keeping other routers in their previously positions and considering the new position of router i.

Stopping condition: If the value of the fitness function does not improve after a certain number of iteration (nbtostop), we suppose therefore having reached the optimal.

5. Simulation results

To compare the proposed approach with SA approach, we randomly generate a region with areas of interest and prohibitive areas. We consider a grid of 100x100 with nbtostop=1000 and r=6.The unit is the size of an EA. If size (EA)=20m, the radius will be r=120m, and the grid 2km x 2km=4km². This is realistic since 802.11n routers have a theoretical outdoor transmission range of 250m. We use a number of routers between 1.5*nr_{min} and nr_{min} (1.5*nr_{min},1.4*nr_{min}, 1.3*nr_{min}, 1.2*nr_{min}, 1.1*nr_{min}, nr_{min}). For each number of routers, the two algorithms are run ten times. Both approaches are compared according to the CPU time used for computation, the quality of solutions in terms of coverage percentage of area of interest, and the ability to provide similar results. Tables 1 to 4 in Appendix 2 provide the results of the simulation phase conducted using Scilab 5.4.

Figure 1 provides the coverage percentage of both approaches. In this figure we can observe that the SA approach provides better solutions than the centre of mass (CM) approach in terms of coverage percentage. This can be explained by the fact that in the SA approach, when the temperature is close to the minimal one, the hop distance is reduced, allowing reaching better positions that improve the quality of the solution. But in CM approach, routers are eventually moved to their centre of mass of single coverage.

Another observation concerns the ability to provide similar results by both approaches. We observe a great difference between the best and the worst coverage percentage with the SA approach. For instance, with the number of routers nr=1.2nr_{min}, we observe a variation of about 8% between the maximum and the minimum coverage. But in the CM approach, for each run, the maximum is close to the third quartile while the minimum is close to the first quartile, with those quartiles close to each other. This expresses some ability of CM approach to provide similar results. Finally concerning the CPU time used, the CM approach in all configurations are in average ten times more efficient than SA approach, as we can observe in Figure 2. This is important when we are dealing with online optimisation in which we would like to observe a solution in very short time.

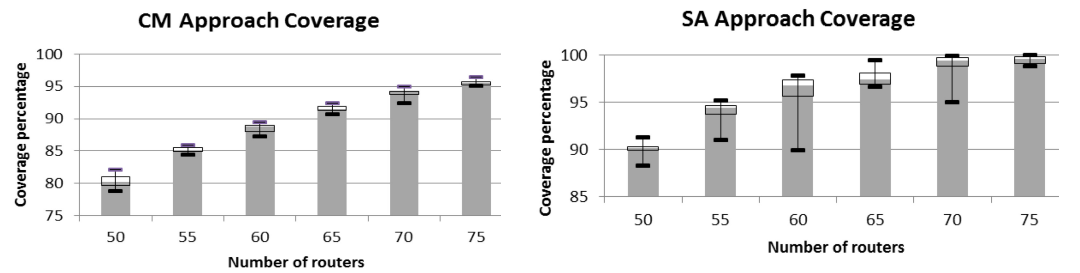

Figure 1: Coverage percentage provided by CM and SA approaches

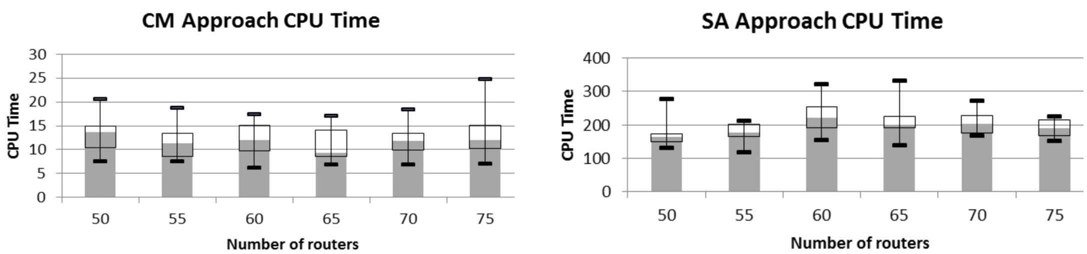

Figure 2: CPU time used by CM and SA approaches

6. Conclusion and future work

This paper has introduced a new approach based on the calculation of the centre of mass (CM) for the placement of mesh nodes in rural wireless mesh networks. This approach has been compared to simulated annealing. Simulation results have shown a rapid convergence of CM approach compared to SA. In fact CM is in average ten times faster than SA. This is suitable for online optimisation problems where convergence time should be minimised. We also observed an ability of CM approach to provide similar solutions when comparing to SA. However, SA approach provides better solutions.

Further investigation will be conducted to design a new approach combining CM and SA approaches in order to take advantage of the stability and the rapid convergence of CM approach, and the quality of solutions in terms of coverage percentage provided by SA approach. The new approach could be also used for the problem of sensor placement in wireless sensor network.

7. Bibliography

[1] I. F. Akyildiz, X. Wang, and W. Wang. Wireless mesh networks: a survey. Computer Networks 47(4) (2005), 445-487.

[2] Bernardi, G., Marina, M.K.,Talamona, F., Rykovanov, D.: IncrEase: A tool for incremental planning of rural fixed Broadband Wireless Access networks. In: IEEE Global Telecommunications Conference (GLOBECOM 2011), pp. 1013-1018.

[3] Fendji, J.L.E.K., Thron, C., Nlong, J.M.: A Metropolis Approach for Mesh Router Nodes placement in Rural Wireless Mesh Networks. Journal of Computers.10 (2), pp. 101-114, (2015).

[4] Fendji, J. L., Thron,C., and Nlong, J. M.: Simulated Annealing approach for mesh router placement in rural Wireless Mesh Networks. 7th International Conference, AFRICOMM 2015, Cotonou, Benin, December 15-16, 2015.

[5] Benyamina, D., Hafid, A.,Gendreau, M.: Wireless mesh networks design—a survey. IEEE Communications Surveys & Tutorials 14(2), pp. 299-310 (2012).

[6] Xhafa, F., Sánchez, C., Barolli, L.: Genetic algorithms for efficient placement of router nodes in wireless mesh networks. In: 24th IEEE International Conference onAdvanced Information Networking and Applications (AINA), pp. 465-472(2010).

[7] Li, F., Wang, Y., Li, X. Y., Nusairat, A., Wu, Y.: Gateway placement for throughput optimization in wireless mesh networks. Mobile Networks and Applications, 13(1-2), 198-211(2008).

[8]De Marco, G. (2009, September). MOGAMESH: A multi-objective algorithm for node placement in wireless mesh networks based on genetic algorithms. In 6th IEEE International Symposium onWireless Communication Systems(ISWCS 2009), pp. 388-392 (2009).

[9] E. Amaldi, A. Capone, M. Cesana, I. Filippini, F. Malucelli. Optimization models and methods for planning wireless mesh networks. Computer Networks 52 (2008) 2159-2171.

[10] Xhafa, F., A. Barolli, C. Sánchez, L. Barolli. A simulated annealing algorithm for router nodes placement problem in Wireless Mesh Networks.Simulation Modelling Practice and Theory, In Press, 2010.

[11] J. Wang, B. Xie, K. Cai and D.P. Agrawal. Efficient Mesh Router Placement in Wireless Mesh Networks, MASS 2007, Pisa, Italy (2007).

[12] Xhafa, F., C. Sanchez, and . L. Barolli, Genetic Algorithms for Efficient Placement of Router Nodes in Wireless Mesh Networks in Advanced Information Networking and Applications (AINA), 2010 24th IEEE International Conference on p. 465-472.

[13] Fendji, J.L. E. K.,Thron,C., &Nlong,J.M.: Mesh router nodes placement in rural wireless mesh networks. In M.Sellami, E.Badouel, &M.Lo (Eds.), Actes du CARI 2014 (ColloqueAfricain Sur LA Recherche en InformatiqueetMathématiquesAppliquées). Inria:Colloques CARI, pp. 265-272.

Appendix 1

Basic algorithm of Simulated Annealing

Algorithm 2: Simulated annealing

Input: f : the objective function to be minimised
Output: s: the best solution found

```
Begin
  T := T_initial ; s:= InitialSolution(); v:= f(s)
  while (stopping condition not met) do
    while (equilibrium condition not met) do
      s' := GenerateSolution()
      v' := f(s')
      ΔE := v' − v
      if ΔE ≤ 0 then s := s'
      else accept s' with probability e^(−ΔE/T)
    Update(T)
  return s
End
```

Particularisation of the SA algorithm

Initialization

Routers are placed randomly in areas of interest in the region during the initialization phase.

Cooling schedule

The initial temperature T=10. A geometric update scheme with α=0.5 has been selected. When the temperature is less than T_{min}=0.01, the cooling process stops.

Move

Only one router is moved at the same time, in a randomly selected direction and distance. The movement from the current EA_a to the new EA_b is simulated if and only if *Cover*(EA_b)=1 and *Place*(EA_b)=1. Initially great moves are selected to allow a rapid convergence. The size of moves decreases with the temperature; when the temperature is close toT_{min}, the size of moves is one EA.

Fitness function

We also count the number of EAIs that are covered to evaluate the fitness function. This is done by (7) after the initialisation.

Acceptance criterion

When $C_b \geq C_a$, the coverage change is directly accepted. But when the coverage change is negative, the change is accepted with a certain probability following the Boltzmann distribution and influenced by the temperature $T$to avoid local optimum.

Equilibrium state and stopping condition

The equilibrium state is supposed to be reached if after a number (stop) of moves no solution has been accepted. The stopping condition depends on Imp and on T_{min}. At each temperatureT_i, Imp indicates whether the solution has improved. When the equilibrium state at a temperature $T_i$is reached, before decreasing the temperature we check whether the solution has improved. In case of an improvement, we decrease the temperature and move to the next iteration. But if there is no improvement or the temperature is less than T_{min}, we stop the search process and suppose having reached an optimum.

At the beginning nr_{min} routers are used. The SA algorithm is running *nRun* times at each stage. If the required coverage is satisfied, we remove one router and restart until the coverage can no longer be satisfied.

Appendix 2

Data from simulation

Routers		Run1	Run2	Run3	Run4	Run5	Run6	Run7	Run8	Run9	Run10
$1.5nr_{min}$	75	9,17	24,80	11,99	9,67	18,92	7,06	11,74	14,03	15,51	11,92
$1.4nr_{min}$	70	11,69	11,94	6,90	7,37	9,88	18,42	10,12	14,59	13,85	12,40
$1.3nr_{min}$	65	6,91	12,88	8,18	17,07	8,33	14,47	9,47	17,07	9,14	9,19
$1.2nr_{min}$	60	15,13	14,82	8,65	17,47	12,06	10,71	16,88	12,08	9,50	6,19
$1.1nr_{min}$	55	12,19	11,72	13,79	10,72	7,70	16,30	11,03	7,95	18,71	7,51
nr_{min}	50	13,84	8,36	13,36	15,29	12,48	17,44	9,70	7,50	20,56	14,03

Table 1: CM Approach CPU Time

Routers		Run1	Run2	Run3	Run4	Run5	Run6	Run7	Run8	Run9	Run10
$1.5nr_{min}$	75	196,27	223,42	222,76	224,51	174,66	186,27	151,42	195,63	165,97	165,84
$1.4nr_{min}$	70	203,54	243,02	187,52	173,54	166,77	167,72	201,57	202,68	271,51	237,25
$1.3nr_{min}$	65	192,30	216,68	192,75	168,92	201,00	138,45	281,63	198,06	229,91	333,49
$1.2nr_{min}$	60	322,46	266,62	217,05	154,74	195,34	244,87	186,72	257,85	189,71	224,98
$1.1nr_{min}$	55	204,20	167,72	212,28	119,11	165,88	206,61	197,04	174,12	179,18	154,24
nr_{min}	50	147,71	130,44	182,64	159,86	147,97	277,46	172,26	169,05	172,86	154,45

Table 2: SA Approach CPU Time

Routers		Run1	Run2	Run3	Run4	Run5	Run6	Run7	Run8	Run9	Run10
$1.5nr_{min}$	75	95,17	95,77	95,04	95,54	95,20	95,99	96,40	95,47	95,53	95,44
$1.4nr_{min}$	70	93,96	94,35	93,69	92,39	94,97	94,31	93,49	94,19	94,08	94,21
$1.3nr_{min}$	65	91,41	91,66	90,80	92,41	90,68	92,32	91,41	91,28	91,48	92,01
$1.2nr_{min}$	60	89,21	89,00	87,93	88,82	89,41	88,91	88,71	87,50	88,00	87,27

$1.1nr_{min}$	55	84,92	84,49	85,40	85,13	85,04	85,52	84,99	84,92	85,95	85,86
nr_{min}	50	80,37	79,66	80,19	81,14	82,17	80,73	78,77	78,84	81,26	79,96

Table 3: CM Approach Coverage percentage of area of interest

Routers		Run1	Run2	Run3	Run4	Run5	Run6	Run7	Run8	Run9	Run10
$1.5nr_{min}$	75	99,36	99,88	99,57	98,82	99,06	99,70	99,98	98,89	99,82	99,80
$1.4nr_{min}$	70	99,25	99,57	94,99	99,59	99,75	98,70	99,88	99,75	98,38	99,30
$1.3nr_{min}$	65	98,09	96,86	99,47	96,70	98,77	96,61	97,29	97,52	97,04	98,00
$1.2nr_{min}$	60	95,44	95,29	96,68	97,41	97,41	96,84	97,82	97,06	96,18	89,94
$1.1nr_{min}$	55	92,03	95,19	94,54	94,06	94,29	94,72	91,05	93,64	94,85	94,56
nr_{min}	50	91,28	90,62	90,19	89,89	90,32	88,27	89,41	90,21	90,18	90,00

Table 4: SA Approach Coverage percentage of area of interest