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Abstract: Flat ad hoc architectures are not scalable. In order to overcome this major drawback, hierarchical routing is introduced since it is found to be more effective. The main challenge in hierarchical routing is to group nodes into clusters. Each cluster is represented by one cluster head. Conventional methods use either the connectivity (degree) or the the node Id to perform the cluster head election. Such parameters are not really robust in terms of side effects. In this paper we introduce a novel measure that allows to form clusters and in the same time performs the cluster head election. Analytical models and simulations results show that this novel measure proposed for cluster head election induces less cluster head changes as compared to classical methods.

Key-words: ad hoc, wireless, self-organization, stochastic geometry, scalability

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Auto-organisation dans les réseaux ad-hoc

Résumé : Les architectures à plat n'offrent des possibilités d'utilisation que sur de petites échelles. Dans le but de pourvoir à cet inconvénient, le routage hiérarchique s'est montré efficace. Le principal défi est donc de regrouper les nœuds en groupes aussi nommés "clusters". Chaque cluster est représenté par son chef de cluster. Les méthodes conventionnelles utilisent, entre autres, pour son élection le degré ou encore l'identifiant. De tels paramètres ne sont pas très robustes. Nous proposons ici une nouvelle métrique permettant d'organiser le réseau de façon à pouvoir utiliser un réseau ad hoc sur des échelles plus larges. Les résultats analytiques et de simulation montrent que cette métrique induit moins de changements de topologie que les méthodes classiques.

Mots-clés : ad hoc, auto-organisation, géométrie stochastique, passage à l'échelle

1 Introduction

Wireless ad-hoc networks consist of a set of mobile wireless nodes without the support of a pre-existing fixed infrastructure. Ad hoc networks find domains of application in battlefields coordination or on-site disaster relief management. Each host/node acts as a router and is able to move in an arbitrary manner. This presents a challenging issue for protocol design since the protocol must adapt to frequently changing of network topologies. More recently, researchers are looking in application of ad hoc paradigms in sensor networks which induce to be able to set up a very large number of nodes.

In order to be able to use ad hoc networks on very large scale, flat routing protocol (reactive or proactive) is really not suitable. Indeed, both routing approaches become ineffective for large scale wireless ad hoc networks, because of link (flooding of control messages) and processing overhead (routing table computation). One well known solution to this scalability problem is to introduce a hierarchical routing by grouping geographically close nodes to each other in clusters and by using an "hybrid" routing scheme: classically proactive approach inside each cluster and reactive approach between cluster [12, 14]. Such an organization also presents numerous advantages as more facility to synchronize stations in a group or to attribute new service zones.

In this paper we propose a novel metric suitable for organizing an ad hoc network into clusters and we propose a new distributed cluster head election heuristic for an ad hoc network. Our new metric does not rely on "static" parameters and thus our novel heuristic extends the notion of cluster formation. The proposed heuristic allows load balancing to insure a fair distribution of load among cluster heads. Moreover, we implement a mechanism for the cluster head election that tries to favor their re-election in future rounds, thereby reducing transition overheads when old cluster heads give way to new ones. We expect from network organization to be robust towards node mobility. If we want overhead to be reasonable, our organization must change as less as possible when nodes move and topology evolves. Moreover, we would like to be able to apply some localization process and inter-groups routing above our organization.

The remainder of this paper is organized as follows. Section 2 defines the system model and introduces some notations. Section 3 reviews several techniques proposed for cluster head selection. Sections 4 and 5 will present our main contribution and will detailed the distributed selection algorithm. Simulation experiments presented in section 6 demonstrate that the proposed heuristic is better than earlier heuristics. Finally, we present our conclusion in section 7 where we discuss possible future areas of investigation.

2 System model

In an ad hoc network all nodes are alike and all are mobile. There are no base stations to coordinate the activities of subsets of nodes. Therefore, all the nodes have to collectively make decisions and the use of distributed algorithms appears to be mandatory. Moreover, all communication are performed over wireless links. As usual, we will model an ad hoc network by a graph $G = (V, E)$ where V is the set of mobile nodes ($|V| = n$) and $e = (u, v) \in E$ will model a wireless link between a pair of nodes u and v only if they are within wireless range of each other.

For the sake of simplicity, let first introduce some notations. We note $\mathcal{C}(u)$ the cluster owning the node u and $\mathcal{H}(u)$ the cluster head of this cluster. From graph theory textbook book [8] we will also note $\Gamma_k(u)$ the *k-neighborhood* of a node u, *i.e.*, $\Gamma_k(u) = \{v \in V | d(u, v) \leq k\}$ and will note $\delta_k(u) = |\Gamma_k(u)|$.

We will note $e(u/\mathcal{C}) = \max_{v \in \mathcal{C}(u)}(d(u, v))$ the *eccentricity* of a node u inside its cluster and thus the *diameter* of a cluster will be $D(\mathcal{C}(u)) = \max_{v \in \mathcal{C}(u)}(e(u/\mathcal{C}))$.

3 Related work

Researchers have proposed several techniques for cluster formation and cluster head selection. All solutions aim to identify a subset of nodes within the network and bind them a leader. The clusterheads are responsible for managing communication between nodes in their own neighborhood as well as routing information to other clusterheads in other neighborhoods. Typically, backbones are constructed to connect neighborhoods in the network.

Past solutions try to gather nodes into homogeneous clusters by using either an identity criteria (*e.g.*, the lowest Id [9, 3]) or a fixed connectivity criteria (maximum degree [4], max-min D-cluster [1], 1-hop clusters [2, 5, 11], k-hop clusters [6]).

Such past solutions based on a fixed cluster diameter [7, 4, 1], fixed cluster radius [13] or a constant number of nodes [15] are not adapted to large ad hoc networks since they may generate a large number of clusterheads. Therefore, it is desirable to have control over the clusterhead density in the network. Note that previous clustering solutions have also relied on synchronous clocks for exchange of data between nodes. It is the case for example in the Linked Cluster Algorithm [2], but such an heuristic is developed for relatively small number of nodes (less than 100). Solutions based on the degree or the lowest Ids can result in a high turnover of clusterheads when topology changes [10, 7]. Solutions were also envisaged to base the election on a pure mobility criteria [4] but if mobility should be taken into account, electing only non mobile nodes may result in isolated cluster heads, which may be useless.

In all previous works, the design of the cluster selection appears to be similar with few variants. Each node computes locally its own value of a given criteria (degree, mobility...) and locally broadcasts this value in order to compete with its neighbors. All nodes are thus able to decide by their own if they win the tournament and can be declared cluster head. In case of multiple winners, a second criteria (*e.g.*, Id) is used.

4 Main objectives

The main goal is to design a heuristic that would select some nodes as cluster head and computes clusters in a large ad hoc network. As we mentioned in the previous section, the definition of a cluster should not be defined a priori by some fixed criteria but must reflect the *density* of the network. In order to be scalable, the heuristic should be completely distributed and nodes should asynchronously run the algorithm thus avoiding any clock synchronization. The number of messages exchanges should be minimized. In fact, we will use only locally broadcast messages like HELLO PACKET used in order to discover the 2-neighborhood of a node. Finally, in order to ensure stability, it would be preferable not to re-elect cluster head when possible and nodes that are "too" mobile will not participate in the ballot phase.

The criteria metric should gather and aggregate nodes into clusters not on an absolute criteria (like degree or diameter) and thus should be adaptive in order to reflect the ad hoc network. To elect a cluster head, we will need to promote node stability in a way of limiting traffic overhead when building and maintaining the network organization. Secondly, the criteria should be robust, *i.e.* not be disturbed by a slightly topology change. Finally, the criteria should be computed locally by using only local traffic (intra-cluster routing) since it is cheaper that inter-cluster traffic.

Based on these general requirements we propose a novel heuristic based on a metric criteria which gathers the density of the neighborhood of a node. This density criteria reveals to be stable when the topology evolves slightly. As the network topology changes slightly the node's degree of connectivity is much more likely to change than its density that smoothes the relative topology changes down inside its own neighborhood.

5 Our contributions

5.1 The density metric criteria

In this section, we introduce our criteria called *density*. The notion of density should characterize the "relative" importance of a node in the ad hoc network and in its own k-neighborhood. As mentioned earlier, the node degree is not adequate. The density notion should absorb small topology changes. The underlying idea is that if some nodes move in $\Gamma_1(u)$ (*i.e.*, a small evolution in the topology), changes will affect the microscopic view of node u (its own degree $\delta_1(u)$ will change) but its macroscopic view will in fact not change since globally the network does not drastically change and its $\Gamma_1(u)$ remains globally the same. The density is directly related to both the number of nodes and links in a k-neighborhood. Indeed, the density will smooth local changes down in $\Gamma_k(u)$ by considering the ratio between the number of links and the number of nodes in $\Gamma_k(u)$.

Definition 1 (density) *The k-density of a node $u \in V$ is*

$$\rho_k(u) \quad = \quad \frac{|e = (v, w) \in E \,|\, w \in \delta_k(u) \; and \; v \in \delta_k(u)|}{\delta_k(u)} \tag{1}$$

The 1-density (also noted $\rho(u)$) is thus the ratio between the number of edges between u and its 1-neighbors (by definition the degree of u), the number of edges between u's 1-neighbors and the number of nodes inside u's 1-neighborhood .

In the following, we will see that the most robust metric among these different ones is in fact the 1-density, which is also the cheapest in terms of messages exchanges. Indeed, note that to compute $\rho_k(u)$, the node u must know $\Gamma_{k+1}(u)$ since it must be able to compute the number of edges that exist between all its k-neighbors.

5.2 Cluster head selection and cluster formation

5.2.1 Basic idea

Each node computes its k-density value and locally broadcasts it to all its k-neighbors. Each node is thus able to decide by itself whether it is winner in its 1-neighborhood (as usual, the smallest Id will be used to decide between joint winners). Once a cluster head is elected, the cluster head Id and its density is locally broadcasted by all nodes that have joined this cluster. The cluster can then extend itself until it reaches a cluster frontier of another cluster head. The only constraint that we introduce here to define a cluster is that two neighbors can not be both cluster head. This insures that a cluster head will not be too off-center in its own cluster, that a cluster would have at least a diameter of two and that two cluster heads will be distant of at least three hops.

5.2.2 Heuristic

The heuristic process is quite simple. On a regular basis (frequency of HELLO packets for instance), each node computes its k-density based on its view of its $k+1$-neighborhood. To simplify the notation we describe the 1-density heuristic. The k-density is similar since the only modification to be made is gathering the $k+1$-neighborhood which is no more given by sending only HELLO packets locally but at k-hops.

Algorithm 1 Cluster head selection

For all node $u \in V$

$\triangleright$ *Checking the neighborhood*
Gather $\Gamma_2(u)$
if mobility(u, $\Gamma_1(u)$) $>$ threshold **then**
    $\triangleright$ *Checking the 1-neighborhood consistency. If this one changes too much, node u will not participate to the ballot phase since is "relatively" too mobile.*
    break
end
Compute $\rho(u)$
Locally broadcast $\rho(u)$
$\triangleright$ *This local broadcast can be done by piggybacking $\rho(u)$ in HELLO packets.*
$\triangleright$ *It allows node u to be aware of all of its 1-neighbors' density value and to know whether they are eligible.*
if $(\rho(u) = \max_{v \in \Gamma_1(u)}(\rho(v)))$ **then**
    $\mathcal{H}(u) = u$
    $\triangleright$ *u is promoted cluster head.*

▷ ***Note that if several nodes are joint winners, the winner will be the previous cluster head whether it exists, otherwise, the less mobile node, otherwise, the smallest Id.***
$\forall v \in \Gamma_1(u), v \in \mathcal{C}(u)$
▷ ***All neighbors of u will join the cluster created by u as well as all nodes which had joined u's neighbors.***
else
▷ $\exists w \in \Gamma_1(u) | \rho(w) = \max_{v\in\Gamma_1(u)}(\rho(v))$
$\mathcal{H}(u) = \mathcal{H}(w)$
▷ ***Either $\mathcal{H}(w) = w$ and u is directly linked to its cluster head, either w has joined another node x and $\mathcal{H}(u) = \mathcal{H}(w) = \mathcal{H}(x)$.***
▷ ***If there exist k ($k > 1$) nodes w_i such that $\rho(w_i) = \max_{v\in\Gamma_1(u)}(\rho(v))$ and such that $w_i \notin \Gamma_1(w_j) (i \neq j)$ then u will join the node w_i which Id is the lowest and all $\mathcal{C}(w_i)$ (for i=1 to k) will merge consequently.***
end
Locally broadcast $\mathcal{C}(u)$
▷ ***Each node will know whether its 1-neighbors belong to the same cluster as it and whether two of its 1-neighbors belong to the same cluster. This will be useful for the routing process.***

5.3 Maintenance

Given that every nodes are mobile and liable to move at any time, our cluster organization must adapt to topology changes. For this, our nodes have to check their environment periodically and so check their mobility. If they become too mobile, they will not join any cluster, if at the opposite, they were too mobile and now are able to communicate, they will join the cluster of their neighbor which has the highest density. Each node checks periodically its density and its neighbors' one. They continue joining their neighbor which has the highest density. If this last changes, the reconstruction will be automatic without generating lots of additional traffic overhead.

5.4 Analysis

In this subsection we will analyse the average 1-density $\tilde{\rho}_1(u)$ of a node u, then its k-density for $1 \leq k$. We consider a multiple-hop ad-hoc network where nodes are distributed according to a Poisson point process of constant spatial intensity λ. Each node has a transmission range equal to R depending on its transmitting power $\mathcal{P}_u$.

Lemma 1

$$\tilde{\rho}_1(u) = \frac{\lambda^2 \pi R^4 \left(\frac{\pi}{2} - \frac{3\sqrt{3}}{8}\right) - 1}{\lambda \pi R^2 - 1} \tag{2}$$

Proof 1 *There are $\lambda \pi R^2$ nodes in a disk of radius R. Thus, a node u centered in this disk has a degree (number of 1-neighbors) depending of R such that $\delta_1(u) = \delta_R = \lambda \pi R^2 - 1$. For each neighbor v of u located at an Euclidean distance $r, 0 < r \leq R$ from u, the links between*

v and one of the other neighbors of u are the ones between v and the nodes situated in both transmission range of u and v, that means the ones located in the intersection of both disks. The number of these links is the number of nodes in this area minus the node v and minus the node u. The average number of nodes in this full zone is $\lambda A(r)$ where $A(r)$ is the area of the full zone and therefore the numbers of links is $\lambda A(r) - 2$. Moreover:

$$A(r) = 2R^2 \arccos \frac{r}{2R} - r\sqrt{R^2 - \frac{r^2}{4}}$$

Furthermore, we have $2r\lambda\pi dr$ nodes at distance r from u. So, the average number of links between nodes v at Euclidean distance r from u and the u's other 1-neighbors which also are v's neighbors is:

$$(2r\lambda\pi dr) \times \left[\lambda(2R^2 \arccos \frac{r}{2R} - r\sqrt{R^2 - \frac{r^2}{4}}) - 2\right]$$

Then, to have every links we have to count them for all r as $0 < r \leq R$. As each link will be counted twice, we then divide by 2. Finally, the average number of links L between u's 1-neighbors is:

$$\begin{aligned} L &= \frac{1}{2}\int_0^R \left(\lambda\left(2R^2 \arccos \frac{r}{2R} - r\sqrt{R^2 - \frac{r^2}{4}}\right) - 2\right) 2r\lambda\pi dr \\ &= \lambda^2\pi R^4 \left(\frac{\pi}{2} - \frac{3\sqrt{3}}{8}\right) - R^2\lambda\pi \end{aligned}$$

The average number of links to consider is $L' = L + \delta_R$ therefore the average 1-density for a node u is $\tilde{\rho}_1(u) = \frac{L'}{\delta_R}$ ■

Lemma 2

$$\tilde{\rho}_k(u) = \frac{\lambda^2\pi R^4 \left(k^2 \arccos \frac{1}{2k} + \frac{k^4}{2} \arccos \frac{2k^2-1}{2k^2} - \frac{2k^2+1}{8}\sqrt{4k^2-1}\right) - \frac{k^2-1}{2}\lambda\pi R^2 - 1}{k^2\lambda\pi R^2 - 1} \quad (3)$$

Proof 2 *The total number of nodes to consider is the number of nodes in the entire k-neighborhood, so $\lambda\pi k^2 R^2$. Let $\rho_k(u) = \frac{L}{\lambda\pi k^2 R^2}$ where L is the total number of links in k-neighborhood and $L = L_1 + L_2$ where L_1 is the number of links between i-neighbors and L_2 is the number of links from $(i-1)$-neighbors and i-neighbors, and so $\forall i$ such as $0 \leq i \leq k$.*

For a node u, its i-neighbors are nodes situated between a circle of radius $(i-1)R$ and a circle of radius R, both centered on u. Thus, if $v \in \delta_i(u)$ then $d_{uv} = r((i-1)R \leq r \leq iR)$ and the numbers of links between v and $w \in \{\delta_i(u)/v\}$ is the number of nodes in the hatched area ${A_1}_i(r)$ on figure 5.4, minus node v (thus $\lambda {A_1}_i(r) - 1$ nodes). It is to say the intersection between a disk C_r of radius R centered in v and the disk of radius iR centered on u minus the intersection of this same disk C_r with the disk of radius $(i-1)R$ centered in u.

$$\begin{aligned}A_{1i}(r) &= i^2R^2 \arccos\frac{r^2+R^2((i-1)^2-1)}{2irR} + R^2\arccos\frac{r^2+R^2(1-i^2)}{2rR}\\&-\frac{1}{2}\sqrt{(R^2(i+1)^2-r^2)(r^2-R^2(i-1)^2)} - (i-1)^2R^2\arccos\frac{r^2+iR^2(i-2)}{2(i-1)Rr}\\&-R^2\arccos\frac{r^2-iR^2(i-2)}{2rR} + \frac{1}{2}\sqrt{(i^2R^2-r^2)(r^2-(i-2)^2R^2)}\end{aligned}$$

We have $\lambda 2\pi r dr$ nodes at distance r of u, thus, as each link between 2 i-neighbors will be counted twice, we have at last:

$$L_1 = \sum_{i=1}^{k}\frac{1}{2}\int_{(i-1)R}^{iR} 2\pi\lambda r(\lambda A_{1i}(r)-1)dr$$

For each i-neighbor v of node u, number of links from $(i-1)$-neighbors to v is equal to the number of nodes in dark area $A_{2i}(r)$ on figure 5.4, it is to say the intersection between a disk of radius R centered on v and a disk of radius $(i-1)R$ centered on node u.

$$\begin{aligned}A_{2i}(r) = &\quad (i-1)^2R^2\arccos\frac{r^2+iR^2(i-2)}{2(i-1)Rr} + R^2\arccos\frac{r^2-iR^2(i-2)}{2rR}\\-&\quad\frac{1}{2}\sqrt{(i^2R^2-r^2)(r^2-(i-2)^2R^2)}\end{aligned}$$

We have $\lambda 2\pi r dr$ nodes at distance r of u, thus, we have at last:

$$L_2 = \sum_{i=1}^{k}\frac{1}{2}\int_{(i-1)R}^{iR} 2\pi\lambda^2 r A_{2i}(r)dr$$

We obtain:

$$\begin{aligned}L_1+L_2 = &\quad \lambda^2\pi R^4\left(k^2\arccos\frac{1}{2k} + \frac{k^4}{2}\arccos\frac{2k^2-1}{2k^2} - \frac{2k^2+1}{8}\sqrt{4k^2-1}\right)\\-&\quad\frac{k^2-1}{2}\lambda\pi R^2 - 1\end{aligned}$$

■

5.4.1 Example

To illustrate this heuristic, let's take the following example (Fig 2). Let's suppose that the node E is too mobile to be eligible.

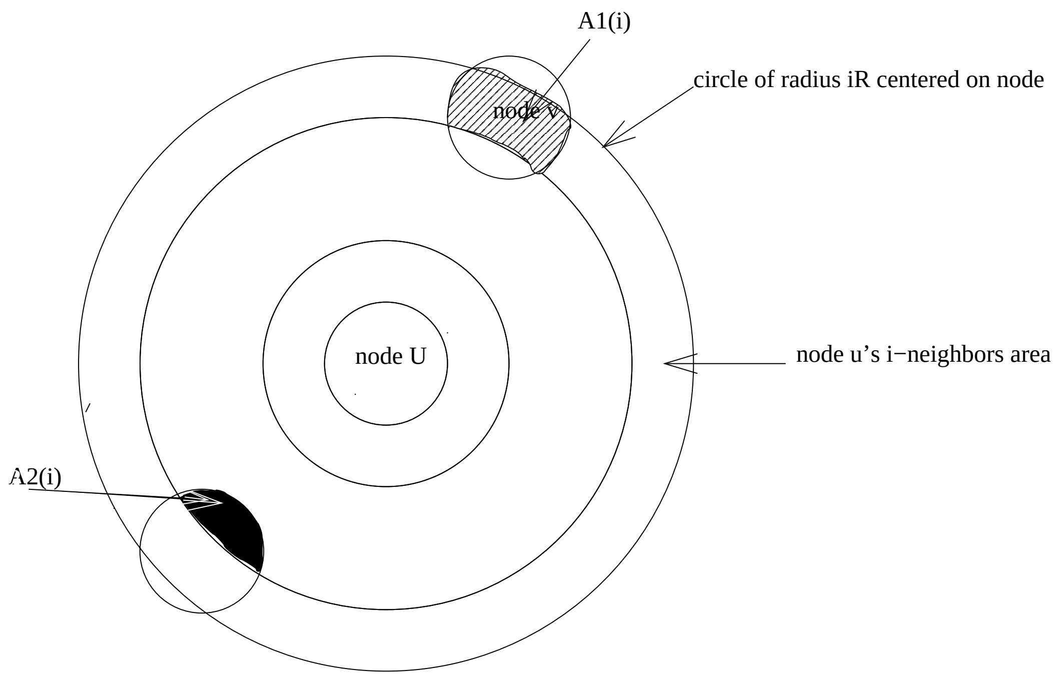


Figure 1: Analytic analyse

Nodes	A	B	C	D	E	F	G	H	I	J
Neighbors	2	4	1	4		2	1	2	3	2
Links	2	5	1	5		3	1	3	3	3
1-density	1	1.25	1	1.25		1.5	1	1.5	1	1.5

Table 1: Results of our heuristics on the illustrative example.

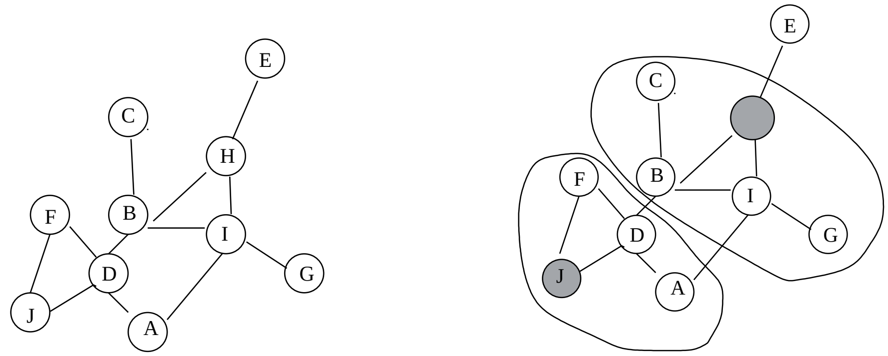


Figure 2: Clustering example.

In its 1-neighborhood topology, node A has two 1-neighbors ($\Gamma_1(\mathrm{A}) = \{D, I\}$) and two links ($\{(A, D), (A, I)\}$); Node B has 4 1-neighbors ($\Gamma_1(\mathrm{B}) = \{C, D, H, I\}$) and five links ($\{(B, C), (B, D), (B, H), (A, I), (H, I)\}$). Table 1 shows the final results.

In the illustrative example, node C joins its 1-neighbor which density is the highest: node B ($\mathcal{H}(C) = \mathcal{H}(B)$). Yet, the node with the highest density in node B's neighborhood is H. Thus, $\mathcal{H}(B) = \mathcal{H}(H)$ and so $\mathcal{H}(C) = \mathcal{H}(H)$. As node H has the highest density in its own neighborhood, it becomes its own cluster head: $\mathcal{H}(H) = H$. To sum up, C joins B which joins H and all three of them belong to the cluster which cluster head is H: $\mathcal{H}(C) = \mathcal{H}(C) = \mathcal{H}(H) = H$. Moreover, we have $\rho_1(J) = \rho_1(F)$. As it is the first construction, none of J and F was cluster head before. If we suppose that J has the smallest Id between both nodes $\mathcal{H}(F) = \mathcal{H}(J) = J$. At last, we obtain two clusters organized around two cluster heads: H and J. (See figure on the right side on figure 2)

6 Simulation and results

We performed simulation experiments to evaluate the performance of the proposed heuristic and compare its behavior against the Highest-Connectivity (Degree) [4]. The geometric approach used allows one to model the spatial organization of networks. As in section 5.4, nodes are randomly deployed using a Poisson process in a 1×1 square ($1km^2$) with varying levels of intensities λ (and thus number of nodes) varying from $750km^{-2}$ to $5000km^{-2}$ which gives on average 750, 3000 and 5000 nodes above our simulation square environment. Two nodes are said to have a wireless link between them if they are within communication range of each other. The communication range R is set to 0.15km in all tests. Some of the more noteworthy simulation statistics measured were: Number of Clusterheads, Cluster Diameter, Nodes Eccentricity in its cluster and Cluster Stability. These statistics provided a basis for evaluating the performance of the proposed heuristic. In each case, each statistic is the average over 100 simulation runs.

Theoretically, within a Poisson process, we can estimate that for 750 nodes, we will have, in average, $\sqrt{750} = 27.4$ nodes by lines. Thus, the distance between two nodes will be in average $(27.4)^{-1} \approx 0.04km$, which is below the transmission range. So, in each line, we can expect from 6 to 7 hops (0.15^{-1}). If a node is promoted clusterhead, every node in its transmission range will join its cluster so we can expect at most 3 different clusterheads by side and so, *at most*, 9 clusterheads in the whole environment. We, indeed obtain less than 9 clusters in each case (See Table 3).

	750 nodes		3000 nodes		5000 nodes	
	Theory	Simulation	Theory	Simulation	Theory	Simulation
mean degree	52	52.31	211	211.6	352	352.87
mean 1-density	16	15.06	62	62	104	103.15
mean 2-density	19.97	20.60	82.10	83.40	139.20	138

Table 2: Average degree and density of nodes.

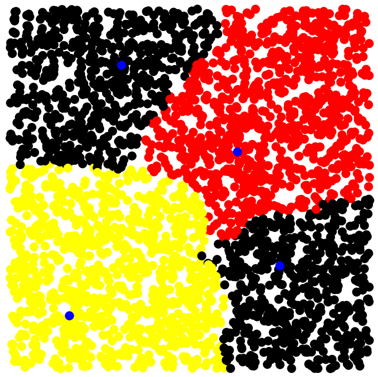
Results in table 2 compare both theoretical analysis and simulated results and they match perfectly.

6.1 Clusters characteristics

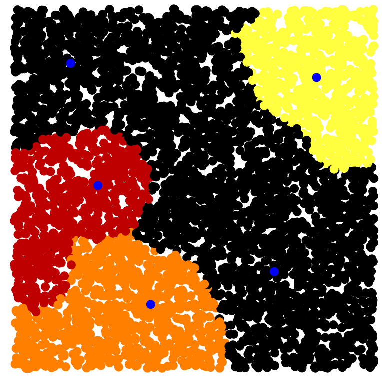
	750 nodes	3000 nodes	5000 nodes
Number of clusters	4.67	4.23	4.42
Number of nodes by cluster	172.5	831	1177.4
$D(\mathcal{C})$	7.1	9.25	9.4
$\tilde{e}(u/\mathcal{C})$	4.86	6.21	6.02

Table 3: Cluster characteristics for 1-density.

Major characteristics of clusters and cluster heads are presented in table 3. Note that our heuristic based on the 1-density is very scalable: when the number of nodes increase significantly (from 3000 to 5000) and the node eccentricity remains the same, the number of clusters is stable. Figure 3 plots one example of cluster organization result obtained during a simulation run. We can notice that clusters are homogeneous and correspond to what we expected: clusterheads are well distributed over the environment in a homogeneous way. Clusters gather close nodes with high connexity in order to favor intra-cluster traffic.



(a)



(b)

Figure 3: Examples of cluster organization for 3000 (a) and for 5000 nodes (b).

6.2 Densities comparison

We then performed simulations in order to choose which k-density offers better results and thus what kind of information on the $k+1$-neighborhood is needed. We also want to compare our density metric to the degree criteria. Thus we first compare cluster formation when using 1-density and 2-density (see table 4(a)).

	750 nodes		3000 nodes		5000 nodes	
k-Density	1	2	1	2	1	2
Nb clusters	4.67	3.01	4.23	2.53	4.42	2.43
$D(\mathcal{C})$	7.1	9.72	9.25	11.67	9.4	12.15
$\tilde{e}(u/\mathcal{C})$	4.86	6.45	6.21	7.03	6.02	8.42

(a)

	Mean	Min	Max
1-density	7.5	2	13
2-density	9.4	4	14
degree	8.1	6	11

(b)

Table 4: (a)Densities comparison over clusters characteristics (b) Number of clusters re-built after 10 movements of 100 nodes.

We can note that results show that 2-density builds less clusters and so that a node is more eccentered in its cluster than with 1-density. So, communications intra-clusters may have a longer latency. In order to discriminate further both densities, we performed simulations and comparisons under node mobility. Indeed, the most interesting density will be the one which offer the best stability and thus limits control traffic overhead over the network for construction and node localizations. For this, we make 100 nodes move randomly and reconstruct clusters over the new distribution in order to compare before and after the movements. These 100 nodes randomly chosen can move in a random direction in a radius from 0 to 0.15.

We are above all interested in clusters stabilities, that means that we expect that the clusterheads remain clusterheads as long as possible. Indeed a cluster is defined by its clusterhead, other nodes can migrate from one cluster to another one, this will not break the cluster. Then, the most noteworthy factor is number of changes among clusterheads. The values in table 4(b) correspond to the average number of cluster heads which had changed along the simulation, so the number of clusters re-formed.

We can notice that the 2-density reconstructs more often clusters than the 1-density. Moreover, as eccentricity and diameter are bigger with 2-density, communications intra-clusters may be more expensive than with 1-density. Thus, 1-density is more stable, more robust than 2-density and, moreover, it is cheaper as it needs only its 2-neighborhood knowledge (given by local HELLO packet) and not further. Then, 1-density is the one we conserve.

6.3 Comparison with the degree heuristic

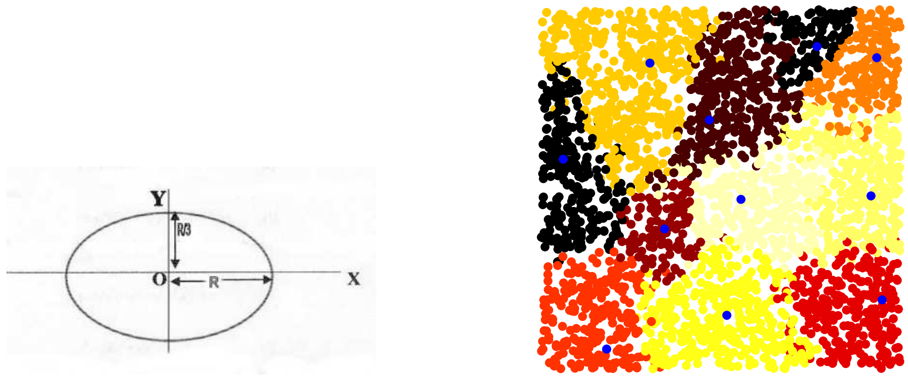
In the same way, we have wished to compare our metric behavior toward node mobility with the one that a clusters formation based on node degree (like in [4]) would have. For this, we realized the same experiment that with 2-density. Table 4(b) presents the results. Once again, we can note that our metric presents the best behavior since it is the one which rebuilds the smaller number of clusters.

6.4 Remarks

To go further, we test our algorithm over a node distribution where node covering is not a disk but an ellipse. Ellipses will have a big axis equal to $2R$ (as for the disk previous used), a small axis to $2*(\frac{R}{3})$ and a random orientation. The covering area will be $\pi R \times \frac{R}{3} \equiv \pi \frac{R^2}{3}$, that is to say 3 times less than the circles transmission range area, which means that, in average, each node has 3 times less neighbors. That is to say that, analytically, we should build three times more clusters. Simulations confirm this results and even with a transmission area which is not a disk, clusters are built with the same good characteristics.

7 Conclusion and perspectives

We have proposed a distributed algorithm for organizing ad hoc (or sensor) nodes into a flexible hierarchy of clusters with a strong objective of not using fixed and non adaptative criteria. We have shown by simulation and analytic analysis that our metric based on the



(a) (b)

Figure 4: Ellipse form covering and resulting cluster formation.

density gathers the dynamics of node neighborhood and outperforms classical static criteria used in past solutions (e.g., max degree).

In future, we intend to test deeper our metric and its behavior over different environments. We have started to study it thanks to stochastic geometry and Palm distribution theory. Our first results tend to show that formed clusters are closed to Voronoi tessalation and thus we can expect to derive promising properties of such organization. We also intend to propose a way of routing and thus perform node locating over such a hierarchy. We are currently investigating the use of purely distributed hash function in order to solve this key problem.

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