Performance Evaluation of a Stability-Oriented Clustering Protocol for Ad Hoc Networks using different Mobility Models

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Abstract

In wireless, infrastructure-less, self-organizing and multi-hop networks - generally termed 'Ad Hoc' - several clustering protocols have been designed to establish a virtual infrastructure in an otherwise flat network, thus enhancing communications reliability and network management efficiency. However, the usefulness of such hierarchical organizations strongly depends on how often they need to be refreshed because of hosts' movements: for that reason, any clustering scheme should be conceived to cope with nodes' mobility. In this paper, we test, by means of computer simulations, how a carefully-designed clustering scheme – i.e. a protocol which correctly takes into account the scenario peculiarities and the fact that organized nodes may move over time – is effective in dominating the network dynamism, no matter what mobility model and mobility rates are chosen.

1. Introduction

Ad Hoc Wireless Networks, which are somehow the new frontier in the wireless networking field and one of the keys for the "everywhere, every-time and any-to-any" connectivity paradigm, are just a collection of mobile and/or fixed nodes that exchange packets in a peer-to-peer fashion, establishing direct wireless links among them. Such infrastructureless networks, being based on cooperation and multihopping, fit greatly in environments where a rapid and quick deployable as well as auto-reconfigurable wireless transmission system is needed, and/or where it is too expensive, ineffective, unneeded, difficult or even impossible to deploy a fixed one.

Given their peculiarities, such networks require protocols explicitly designed for them, such as those usually called Clustering Schemes. They are distributed algorithms able to select nodes and/or group them into subsets, thus creating a virtual hierarchy inside an otherwise flat network; this kind of protocols does not have any counterpart in traditional 'infrastructured' networks, where the hierarchy is implicitly set up between hosts and the fixed infrastructure itself. In ad hoc networks, such virtual organizations represent a way to improve the communications reliability, the network management effectiveness and sometimes the QoS provisioning; quite usually, their main target is to "dominate" the network dynamism, allowing both the set up and the management of cluster-by-cluster instead of node-by-node paths [1].

From this point of view, the mobility, which is usually a common feature of ad hoc networks, should be obviously taken into account by clustering schemes, also considering the characteristics of the scenario they are designed for. In [2] a new clustering protocol, named AC (Availability Clustering), has been defined considering mobility-related issues in a quite general framework, that is to say, the possibility for nodes to be heterogeneous in terms of connectivity, available energy and relative mobility. The scheme's performance and its dependence from protocol's parameters have been evaluated in a given scenario, showing how its effectiveness in building the hierarchy infrastructure may be enhanced through a careful protocol design, tightly coupled with scenario's peculiar characteristics.

The target of this paper is to push the study a step further: the final goal is to estimate the scheme robustness to different variable topology conditions – caused by the degrees and patterns of mobility –, thus proving the effectiveness of a carefully-defined clustering protocol under different mobility scenarios.

The rest of the paper is organized as follows. Section 2 gives an insight into the clustering protocols state-of-art and the impact of mobility on nodes' organization. Section 3 provides an overview of the Availability Clustering and simulation results are described in Section 4. Finally, conclusions and some possible future works are depicted in Section 5.

2. Clustering and mobility, related works

Clustering in wireless ad hoc networks is a way to dominate an otherwise too complex problem (the network management) by splitting it in a number of smaller and simpler sub-problems. It naturally follows that clustering schemes can be thought as useful not by their own, but in the view of supporting other protocols (e.g routing [4],[5] and MAC [6] ones), which can base their operations on the created infrastructure.

Consequently, it appears clear why such approach has received a lot of interest during the last years, leading to the presentation of a great number of different clustering algorithms, whose differentiation generally lies on the kind of hierarchical infrastructure topology they establish. Most of these schemes group nodes into (overlapping or not) subsets, called clusters. Some schemes select a node into each cluster as the *clusterhead* (i.e. the group leader), which may be just the cluster representative [7] or, in more complex approaches, the coordinator of intra- and inter-cluster communications [8]. Some other algorithms, instead, let all nodes decide, in a distributed manner, which sets have to be formed and what group they have to join without assigning any particular role to nodes themselves [4], [9], [10]. In case of clusters with a cluster leader, some schemes (e.g. [7], [8], [10], [11]) let nodes enter a set only when they have direct wireless links with target clusterheads; others (e.g. [3]), instead, create multi-hop paths between nodes and related cluster leaders, thus defining less, but more numerous groups – making the CH, on the other hand, less powerful in driving the intra-cluster management process. Another way of introducing a hierarchy is to identify a virtual backbone usually called *Spine* [5], [12], which is a network structure composed of a small number of nodes and links among them, usually set up to centralize many networking functions – like the routing ones.

Given this variety of possible, sometimes really different, clustering approaches and the wide range of scenarios where ad hoc networks may prove themselves useful, it is hard to imagine that a unique clustering scheme could be defined. Therefore a careful examination of target scenarios' peculiarities is essential to design truly effective protocols. Mobility is one (maybe one of the most important) of them. If it is not properly considered during the protocol design, the logic organization may be heavily affected by how network topology changes over time, and, consequently, its actual performance, in terms of stability – here considered the extent the infrastructure itself is influenced by nodes movements –, might be worse than expected, thus greatly reducing the usefulness of having an organizing protocol. Some known clustering protocols adopt a similar approach: [13] uses a new kind of metric measuring terminals' relative mobility to elect CHs; [14] considers the absolute node's mobility as a parameter driving the clustering algorithm; [15] organizes nodes on the basis of how long paths between hosts last.

In [2], a new clustering scheme (named AC, *Availability Clustering*) has been proposed for indoor ad hoc networks composed by several hundreds nodes, supposed to be heterogeneous with respect to both mobility and energy. Such heterogeneity was carefully analyzed and taken into account during the scheme's design to increase the quality of the spine/cluster composition – i.e. the percentage of nodes that better (because of their greater resources) may assume leading roles – and, consequently, to enhance hierarchy stability.

In this paper the goal is to evaluate how the original scheme is effective in building a stable organization also in different nodes mobility conditions. In order to carry out such study, three well known, mobility models were selected: the most used model in literature, i.e. the *Random Waypoint Mobility* (RW) [16], the *Natural Random Mobility* (NR) [17], introducing a correlation between movements steps, and the *Reference Point Group Mobility* (RPGM) [18], for groups' mobility simulations.

3. Overview of AC clustering scheme

AC's design was focused on two main targets, namely: to identify a feasible virtual infrastructure topology and to exploit nodes' heterogeneity to enhance structure stability, by identifying those having more resources and giving them leading roles required by the superimposed hierarchy. In the following, a brief overview of AC clustering protocol is given; in [2] a more exhaustive description can be found.

From the infrastructure topology point of view, AC creates an organization like the clustering scheme here named DR [3] does. It splits the network into large clusters, each one with its own spine inside (like [19]). In each cluster, a node elects itself as clusterhead (CH in the following), and other stations can be members of a cluster only if they are at most R hops far away from the CH. Each member chooses one of its neighbors, member of the same cluster, to be its Next Hop (NH in the following), that is the preferred node through which the CH can be reached (def. CH R-feasible or R-reachable); the selected NHs (among which there is the CH itself) and the links among them form the intra-cluster spine, a virtual backbone able to support main networking functions.

Each node individually evaluates its own *Availability Factor* (AF in the following, similar to the one proposed in [14]), defined to measure how "good" at assuming leading roles a node is, using the following formula:

$$AF = \alpha \cdot CF + \beta \cdot EF + \gamma \cdot MF \tag{1}$$

where CF (*Connectivity Factor*), EF (*Energy Factor*) and MF (*Mobility Factor*), ranging in [0,1], estimate the importance of the node with respect to connectivity, energy and mobility. Connectivity has been considered to minimize the number of selected NHs, while energy and mobility were chosen because leading roles should be obviously assigned to nodes having more energy and less relative mobility than others. The three parameters in (1) may be arbitrarily chosen, freely tuning the impact of each node's feature; given our selected scenario, the highest weights have been assigned to EF and MF.

All the three factors are calculated taking into account information belonging to the node and its neighbors only. MF is based on the metric described in [13], which estimates the relative mobility by only considering packets' received power levels (avoiding, by the way, the use of any "external" systems like the GPS, *Global Positioning System*). CF and EF, instead, exploit the Dominating Value concept [20] – i.e. the number of neighbors which have smaller resources levels than the node itself – normalized to the number of neighbors. Here, the estimation of node's characteristics is purely local and relative and makes the algorithm not only simple, but also scalable with respect to the overall network dimensions.

As far as the protocol mechanisms are concerned, AC has been thought to be "lightweight", based only on a periodic information exchange among neighbors through broadcast packets called *beacons* – which also allow the nodes' presence signaling. Protocol operations are supported by two data structures (managed by each node): a 'status array', carrying clustering-related information (node's IDentifier, node's AF, identifier of the node's CH, CH's AF, identifier of the node's NH, MINimum AF within the path towards the CH, Number of Hops on the path towards the CH) and a 'neighbors table', storing data received from neighboring nodes (plus extra information like received power levels related to currently and previously received beacons). Each beacon carries the node's status array, its current energy level and its number of neighbors.

The algorithm behavior is driven by a *Waiting Timer*: when it is pending, the node collects beacons coming from its neighbors, refreshing the related neighbors table entries; when it expires, the node processes all the information, evaluates its own AF, decides its role in the clustering structure, assembles and transmits its beacon.

The decision of the node's role in the clustering structure leads to three possible states, i.e. Initial (INst), Normal (NMst) or Clusterhead (CHst). In INst – which is also the node's starting state – the terminal has not yet joined any cluster. In CHst it has elected itself as the cluster leader. In NMst the node is just member of a cluster and it is either a NH or a leaf node, respectively if it has neighbors that have chosen it as NH or not. State transitions are driven by the station's own AF value and both states and AF values of its neighbors, with the target of enhancing as much as possible the quality and stability of the hierarchy organization, by avoiding any unnecessary structure changes.

In INst, the node affiliation to an existing cluster follows a novel approach, oriented to the infrastructure stability, aiming to choose not the best CH but the hopefully best node-CH path. For all the possible (if any) paths (i.e. NH chain) from itself to all the reachable CHs, the node selects a NH leading to the CH through a path that maximizes the following generic target function:

$$AF_{target} = f(AF(CH), AF(NH), AF_{min}) \tag{2}$$

where AF(CH), AF(NH) and AF_{min} are, respectively, the candidate CH's AF, the candidate NH's AF and the smallest AF on the path. The AF of the selected CH is directly matched with the node's own AF: if the former is greater than, or equal to, the latter, then the node joins the cluster, going to NMst. Otherwise, the node checks its neighborhood, looking for nodes in INst having a greater AF: if so, it stays in INst, waiting for another node to become CH; if not so, it goes into CHst. Here, like in [2], $f(\cdot)$ of (2) has been set equal to the sum of the three arguments.

In NMst, the node goes into INst if it has lost its NH to the previous CH and is unable to find another suitable NH to the same or other CH. Otherwise, if the current NH is still "alive", the scheme behaves differently if the node belongs to the spine or not. In the former case, the node is forced to maintain its affiliation, limiting spine changes and enhancing the infrastructure stability. In the latter case, it always tries to find, if possible, a new better aggregation – i.e. hopefully more stable –. In other words, it looks for a new NMst-node, candidate NH towards the same or other CH, which maximizes (2) and satisfies

$$AF_{target,new} - AF_{target,old} \geq \tau \tag{3}$$

where the threshold τ (similarly to what described in [11]) has been introduced to limit hierarchy variations: higher values mean less aggregation updates. The equation (3) says that, before performing an affiliation change, any node must verify whether the new spine branch is really better than the old one; if not, it could not be convenient to modify the established organization, because of the overhead such variation could imply on other protocols of the same or other layers based on the clustering organization.

In CHst, the node turns back to INst when it has no more neighbors, or when one or more CHs with a higher AF become neighbors (becoming a NMst-member of the newly formed cluster). In [2] a threshold to put a limit to such changes has been also introduced, but the simulations shown that it was of no use, and, for that reason, it is not taken into account.

4. Performance evaluation

The main characteristics of simulations, which have tested both AC and DR schemes, are briefly reported in table 1. The DR has been chosen for its similar spined cluster structure, even if it does not explicitly exploit nodes heterogeneity.

The selected performance metrics are related to the infrastructure topology, the aggregation and the permanence times. The topological metrics embrace the average number of clusters (or CHs) and spine nodes, together with their compositions (percentage of plugged, unplugged, and mobile nodes), and give a view of the quality of the cluster/spine composition. The aggregation time and the permanence time metrics are, respectively, the average time for a node to be aggregated to a CH or to a NH towards a CH, and the average time for a node to retain its role (e.g. CH); they let estimate the degree of stability of the virtual infrastructure.

All these metrics are measured for both AC and DR with the aforementioned mobility models, parameterized by V_{max}. Here the main goal is not to determine what mobility model impacts less than others on the clustering performance, but to understand how the clustering scheme keeps its effectiveness, no matter how nodes are moving. An extensive simulation campaign was carried out combining several values of velocity and AC's τ threshold and the results are differentiated by node typology. Space limitation is the reason why only a subset of the obtained diagrams is reported here.

In the following, each one of the aforementioned metrics, using τ as a parameter and with the minimum value for V_{max} (i.e. 1 m/s), are firstly analyzed. Then, the same metrics are evaluated using V_{max} as a parameter and fixing a suitable τ's value.

Table 1. Simulation parameters.

Simulation Tool		Network Simulator 2 [21]
Network Area		500 m x 500 m
Nodes	Number	1,000
	Composition	60% Mobile (M), 30% Fixed & Unplugged (U), 10% Fixed & Plugged (P)
	Displacement	Random for Mobile, Grid for Fixed
Mobility Models		RW, NR, RPGM (separate simulation campaigns)
Max Velocity (V_{max})		1 m/s ÷ 3 m/s
Initial Energy Level		100 J ÷ 1,000 J
Energy Consumption		P_{TX} = 760 mW, P_{RX} = 395 mW, P_{IDLE} = 1 mW (no depletions)
MAC		Ideal (no collisions)
Channel Model		$\propto d^{(-1/\alpha)}$ (d=distance, α=4.5) [22]
Transmission Range		75 m
Communication Link		Symmetric
Simulation Run Time		1,200 s
Transient Time		100 s
95% Confidence Intervals' Widths		Small percentages of the reported values
Cluster Radius (R)		3 hops
AC τ threshold		0 ÷ 2.5

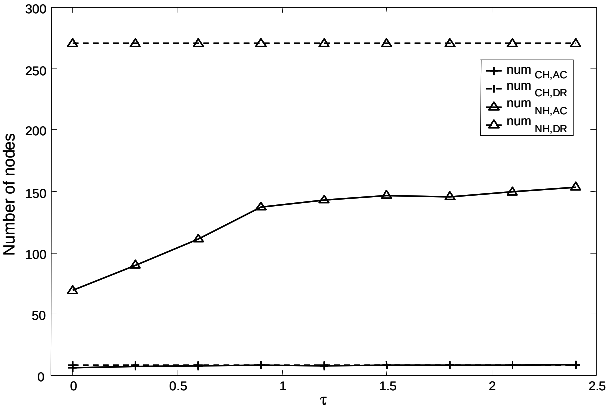

Figure 1 - Average number of CHs and Spine Members (NHs) using RW and fixing Vmax=1m/s.

4.1. Topological metrics using RW

The figure 1 shows the average number of CHs and spine nodes (i.e. NHs) for both AC, with different τ values, and DR, with V_{max}=1 m/s: the above metrics are hereafter briefly indicated as $num_{<role>,<scheme>}$ with <*role*> in {CH,NH} and <*scheme*> in {AC,DR}. Regarding AC, no appreciable variations of $num_{CH,AC}$ can be observed, whereas $num_{NH,AC}$ becomes higher and higher with τ, up to 1.2-1.5, as expected: since τ is the threshold of "convenience" in changing affiliation, then the greater τ is, the less probable an affiliation change is, and, consequently, the higher the number of nodes holding their actual affiliation is. Beyond that limit, the metric's values form a slightly raising set. Also looking at DR, it results that AC tends to form about the same number of clusters as DR (as the overlapping of the relative curves shows in figure 1), while electing much less spine nodes.

The figure 2 is analogous to the figure 1, but with V_{max} variable and τ =1.5. As depicted, the velocity does not sensibly affect the performance of either AC or DR (with respect to the metrics under examination), while AC still outperforms DR in terms of the (reduced) number of

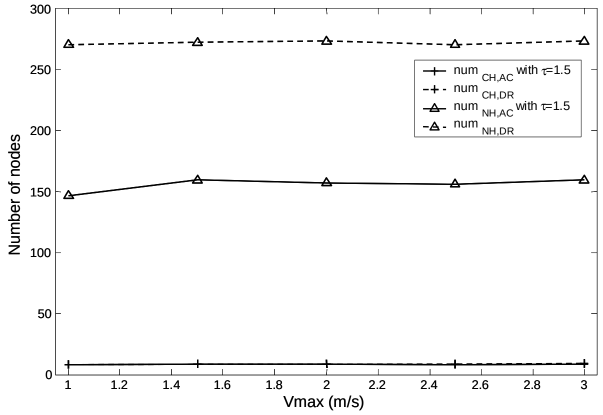

Figure 2 - Average number of CHs and Spine Members (NHs) using RW.

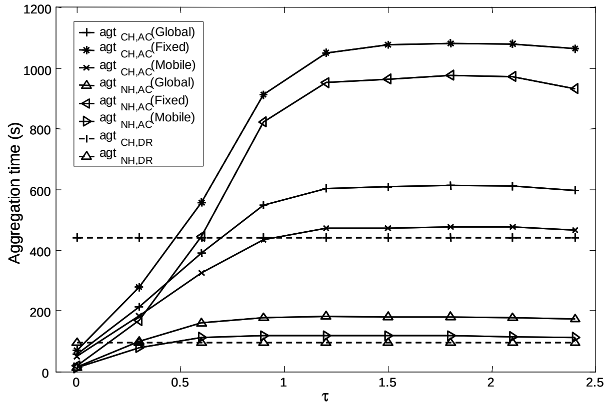

Figure 3 - Average aggregation time to a CH or to a NH using RW and fixing Vmax=1m/s.

spine nodes, though showing quite the same number of CHs. The negligible effect of the motion speed could lie in the RW's peculiarities: in this model, nodes tend to gather themselves in the middle of the network area, which becomes highly dense; therefore, the average number of CHs and spine members, mostly aggregating in this middle region, does not strongly depend on the motion rate.

As proved, also the percentages of plugged (P), unplugged (U), and mobile (M) nodes among both CHs and spine nodes are weakly affected by the mobility. The only remarkable note relates to the different compositions observed for AC or for DR. If AC runs, the best cluster roles (i.e. the spine members) are most likely taken up by nodes provided with the best characteristics (e.g. the energy-unlimited and motion-less ones). In quantitative terms, the CHs 'per-role' distribution is about (P=89%; U=8%; M=3%), without appreciable variations as τ changes. On the other hand, the spine per-role distribution is about (P=45%; U=29%; M=26%) with τ greater than 1.2-1.5: below the specified limit, the distribution is much more unbalanced, in favor of fixed, and specially plugged, nodes. Instead, in case of DR running, the spine composition reflects, as expected, the network's one (P=10%; U=30%; M=60%), since DR does not care about the nodes heterogeneity. The previous evaluations are also extendable to the other V_{max} values.

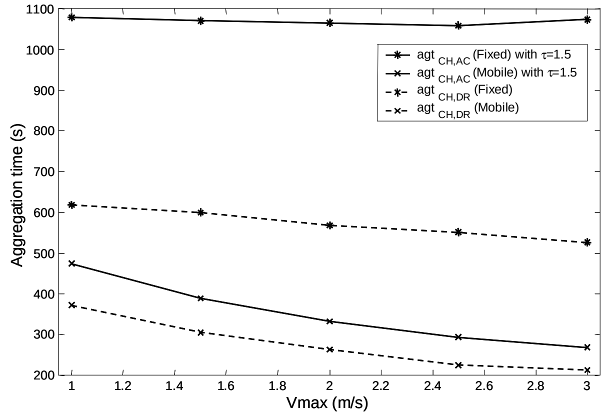

Figure 4 - Average aggregation time to a CH using RW.

4.2. Aggregation time metric using RW

For uniformity, the formalism used here to refer to the aggregation time metric is $agt_{<role>,<scheme>}(<type>)$ with $<role>$ in {CH,NH}, $<scheme>$ in {AC,DR}, and $<type>$ in {fixed, mobile, global}.

The figure 3 shows, with V_{max}=1 m/s, that AC average times become longer and longer as τ extends up to 1.5 and are quite similar if $\tau \geq 1.5$. From here, the previous choice of 1.5 as reference value for τ can be motivated. Such a value was selected to tune AC and to trade off high $agt_{CH,AC}(global)$ and $agt_{NH,AC}(global)$ values with low average number of spine nodes. Continuing in the description of AC's performance, it is worth to highlight that the global average aggregation time does not well describe the real protocol's behavior: as depicted in figure 3, the mobile nodes experience much lower aggregation times than the static ones; adding the fact that the largest contribution to the average aggregation time calculation comes from the mobile nodes, both highlighted aspects lead to a considerable reduction of the global average aggregation time. The figure 3 leads also to note that, with $\tau \geq 1.5$, $agt_{NH,AC}(fixed)$ is comparable with $agt_{CH,AC}(fixed)$. Consequently, the spine paths, composed mainly by fixed nodes, are highly stable (i.e. little dynamic): such stability might be usefully exploited by spine based routing schemes addressing a reliable data delivery. Moreover, still with τ beyond 1.5, $agt_{\cdot,AC}(\cdot)>agt_{\cdot,DR}(\cdot)$, so that the AC spine paths are more stable than those of DR.

As shown in the figure 4, where V_{max} is put on the x-axis and τ=1.5 for AC, the $agt_{CH,AC}(fixed)$ is practically not depending on V_{max}, as it should be obvious, whilst $agt_{CH,AC}(mobile)$ decreases as V_{max} gets higher. This could be interpreted as another proof of the degree of stability of the AC's virtual infrastructure, mostly composed by fixed

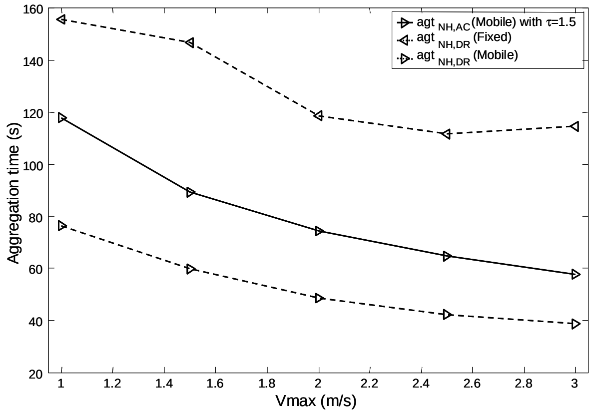

Figure 5 - Average aggregation time to a NH using RW.

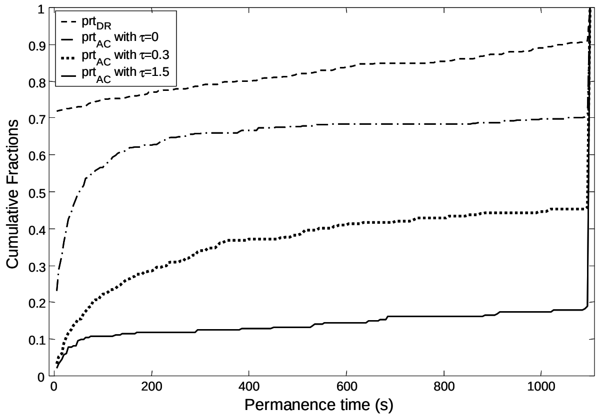

Figure 6 - CH permanence time CDFs using RW and fixing Vmax=1m/s.

nodes as already said. Looking at the DR's plots, the $agt_{CH,DR}(fixed)$ and $agt_{CH,DR}(mobile)$ values can be observed slightly going down in function of V_{max}. This fact may seem odd for fixed nodes, since they should be not influenced by the mobility: in effect, DR does not wisely exploit the nodes' characteristics, including the mobility degree, to aggregate them, so that fixed nodes may be affiliated also to mobile ones and their average aggregation time may be reduced.

Similar comments can be expressed about the figure 5, where V_{max} varies and τ=1.5 for AC. Here, $agt_{NH,AC}(fixed)$ is not drawn for the sake of scaling (i.e. its insertion makes the other plots poorly distinguishable), even considering that this metric goes around 900 s with negligible variations, whatever V_{max} is chosen. Therefore, as well as agt_{CH}, the mobility has no impact on $agt_{NH,AC}(fixed)$, but negatively influences $agt_{NH,AC}(mobile)$ and $agt_{NH,DR}(\cdot)$ (for both fixed and mobile nodes). Once again, the resulting $agt_{NH,AC}(\cdot) > agt_{NH,DR}(\cdot)$ confirms the major stability of AC spines with respect to the DR ones, especially for fixed nodes. More in general, the analysis points out the necessity, in the design of solutions for ad hoc networks, of dealing with the mobility that, otherwise, can cause bad effects on the performance.

4.3. Permanence time metric using RW

As previously seen, AC selects mainly fixed and plugged CHs: the simulations have also proved that such nodes retain their role for about the whole duration of a simulation run. On the other hand, besides the ever lasting CHs, there are few other nodes that sometime assume the CH role and, just after a little time interval, release it. If the metric were evaluated also on the basis of these dynamic contributions, it would lose much significance. Thus, to analyze the real AC's behavior, we plotted in figure 6, fixing V_{max}=1 m/s, the *Cumulative Distribution Functions* (CDFs) of the experimented permanence times for both AC and DR. To respect the formalism already adopted for previous metrics, each CDF is here indicated as $prt_{<scheme>}$ with <*scheme*> in {AC,DR}. In the figure, the sharpness of the AC's CDFs in correspondence of extreme time values reproduces what previously said about the life time of CHs elected by the scheme. Moreover, the greater τ is, the more downward deflected the CDF is: in fact, high values of τ prevent not enough featured nodes to become CHs for short time intervals. In DR, as shown, the CH permanence time assumes low values with much higher probability than in AC, that is to say that the probability of CH dismission is here greater: such aspect, causing more frequent reclustering operations, may penalize the routing performance. Similar conclusions for both AC and DR can be exhibited for higher V_{max} values and are even more evident for plugged nodes.

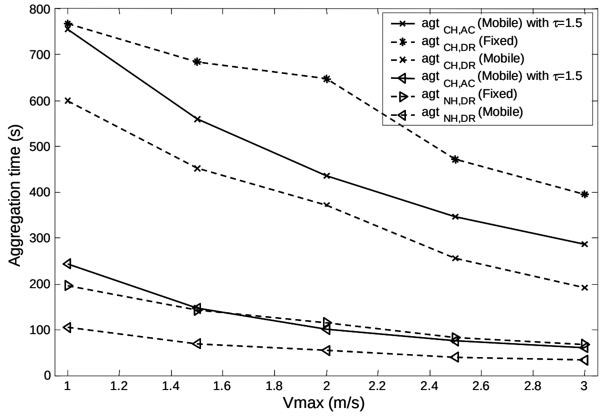

Figure 7 - Average aggregation time to a CH or to a NH using NR.

4.4. Performance using NR and RPGM

Replacing RW with NR in modeling the nodes' mobility, similar trends were found in AC's and DR's performance. Nevertheless, the aggregation and permanence times reflect the fact that NR introduces more dynamism than RW does; in such a way, nodes with NR uniformly distribute themselves within the whole simulation area, thus avoiding typical RW central agglomerations and, as a consequence, reducing links durations. To provide an insight view into performance under NR, the figure 7 depicts the average aggregation time as a function of V_{max}. Again, for analogous considerations expressed concerning $agt_{NH,AC}(fixed)$ under RW, the plots related to $agt_{NH,AC}(fixed)$ and $agt_{CH,AC}(fixed)$ are not reported: both are nearly horizontal straight lines, respectively located at 980 s and at 1070 s.

The performance under RPGM, as well as the related graphics, is similar to those obtained under NR or RW. The RPGM model is based on RW but introduces little more dynamism, since mobile nodes' displacement tends to be constant due to the spatial correlation among different nodes' movements. This reflects on higher CHs number, lower aggregation times to CH and comparable NHs number and aggregation times to NH.

5. Conclusions and future works

This paper has presented a clustering scheme for ad hoc networks that is able to exploit the nodes' heterogeneity to establish a virtual infrastructure within the network. Such infrastructure is formed by spined clusters and characterized by high quality, stability, and adaptivity under different mobility scenarios. Such properties have been proven by means of simulations, letting nodes move according to one out of three well-known mobility models. In addition, comparisons have been made with a similar clustering approach that does not care of the nodes' features: the analysis has shown that our proposal outperforms the second, in terms of some defined metrics. As more general result, we conclude that if the design of a scheme for ad hoc networks does not properly deal with the mobility, it can negatively affect the scheme's performance.

New analysis may be carried out towards different directions. Further studies are required to measure the "goodness" and the "limits" of the AC scheme under different network scenarios. Some complexity and scalability evaluations could help to improve the design of the algorithm. To exploit and validate the virtual infrastructure established by AC, the design of a hierarchical routing scheme able to build routes through the spines, and of a MAC scheme able to differentiate the channel accesses on the basis of a cluster role will follow as well.

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