

A Mobility Based Metric for Clustering in Mobile Ad Hoc Networks¹

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MCL Technical Report No. 01-15-2001

Abstract— This paper presents a novel mobility metric for mobile ad hoc networks (MANET) that is based on the ratio between the received power levels of successive transmissions measured at any node from all its neighboring nodes. This mobility metric is subsequently used as a basis for cluster formation which can be used for improving the scalability of services such as routing in such networks. We propose a distributed clustering algorithm, MOBIC, based on the use of this mobility metric for selection of clusterheads, and demonstrate that it leads to more stable cluster formation than the Lowest-ID clustering algorithm (“least clusterhead change” [3]) which is a well known clustering algorithms for MANETs. We show reduction of as much as 33% in the number of clusterhead changes owing to the use of the proposed technique. In a MANET that uses scalable cluster-based services, the network performance metrics such as throughput and delay are tightly coupled with the frequency of cluster reorganization. Therefore, we believe that since using MOBIC results in a more stable configuration, it will directly lead to improvement of performance.

Keywords: Ad hoc networks, Mobility, Clustering.

¹Proc. IEEE ICDCS 2001 Workshop on Wireless Networks and Mobile Computing, Phoenix, AZ, April 2001.

1 Introduction

If an existing communication infrastructure is expensive or inconvenient to use or setup, or if it is absent, mobile users with wireless connectivity can still communicate with each other by the formation of an *ad hoc* network. Nodes in an ad hoc network can act as both hosts and routers since they can generate as well as forward packets, respectively. Since there is no existing communication infrastructure (e.g., a wired or a fixed wireless base station), ad hoc networks cannot rely on specialized routers for path discovery and routing. Therefore, nodes in such a network are expected to act cooperatively to establish the network “on-the-fly”. Such a network is also expected to route traffic, possibly over multiple hops, in a distributed manner, and to adapt itself to the highly dynamic state of its links and the mobility patterns of its constituent nodes.

Traditionally, the interest in such rapidly deployable network architectures has been for battlefield and disaster relief situations². Military applications such as voice and video communications in the battlefield, and decentralized communication of maps and sensor data fuel research on such network architectures. However, considerable interest in ad hoc networks has been shown recently in the commercial sector owing to the miniaturization of computing devices and proliferation in their numbers, and the increasing demand of people to stay connected all the time. The advent of low power wireless communication technologies such as Bluetooth [1] and HomeRF [8] can propel ad hoc networks to becoming an enabling platform for what is known as *ubiquitous computing* [22].

Communication between any two nodes in an ad hoc network might require the packets to traverse multiple hops. Several protocols have been proposed in the literature for routing in mobile ad hoc networks [19, 12, 7]. Since the intermediate nodes may be mobile, node mobility can cause frequent link failures and staleness of routes. That in turn can result in route errors and trigger off a fresh route discovery process. In some cases, performing a local route repair may be possible[12, 10]. In any case, the effectiveness of any routing algorithm in an ad hoc network depends upon the timeliness and detail of topology information available. In such a scenario, the availability of information which is valid for a longer duration of time is highly desirable.

With the increase in size of the networks, flat routing schemes do not scale well in terms of performance. Routing schemes such as Dynamic Source Routing [12] which discover routes by reactive flooding, and perform well for small networks, can result in low bandwidth utilization in large networks with high load due to longer source routes (and thus, large byte overhead) [11]. Hence, some hierarchical organization is required in large ad hoc networks for solving this problem. Several clustering strategies have been proposed with a focus on imposing a semi-hierarchical structure upon nodes in an ad hoc network in order to increase scalability, improve bandwidth utilization, and to reduce delays for route queries [4, 5, 15, 14]. Routing on top of clustered

²The first infrastructure of its type was the DARPA Packet Radio Network PRNET[13].

topologies [20, 10] is much more scalable than flat routing as it keeps the *flooding* traffic in check.

The basic step in clustering involves formation of easily manageable clusters of nodes. A clustering algorithm known as Lowest-ID (clusterhead selection based on ID) has been proposed in the past [4] and has been revisited later in the “multimedia multihop mobile networks” context [5]. In [3], Chiang et al. have shown that the Lowest-ID algorithm performs better than the max-connectivity algorithm³ in terms of stability of clusters (measured by the number of clusterhead changes), and they have proposed a small change in the Lowest-ID algorithm to improve performance; the improved version is referred to as LCC which stands for “Least Clusterhead Change”.

We believe that since mobility is the main cause for the changes in clusterheads and cluster memberships, it is logical to have a mobility metric as a basis of cluster formation and clusterhead selection. This paper presents a novel mobility metric that is based upon the ratio between the successive measurements of received power at any node from its neighbors. We then present a clustering algorithm, MOBIC, which is similar to the Lowest-ID algorithm, but it uses the new mobility metric for cluster formation. We show by simulations that MOBIC results in more stable cluster formation as it yields as much as 33% reduction in the number of clusterhead changes over the Lowest-ID algorithm (actually its LCC variant).

The rest of the paper is organized as follows: in Section 2, some relevant background and a summary of previous related work is presented. Section 3 describes the approach we have adopted to calculate the mobility metric for each node and outlines the clustering algorithm that is based upon this mobility metric. Section 4 includes a discussion of the results and comparison with previous clustering algorithms. Some directions of future research have been discussed in Section 5. Section 6 concludes the paper.

2 Background and Related Work

2.1 Clustering in MANETs

In any complex distributed system of nodes, *clustering* of nodes into groups results in simplification of addressing and management of the nodes and also yields better performance since details about the remote parts of the distributed system can be handled in an aggregate manner. Thus, imposition of a hierarchical organization is beneficial for the management of a complex system, and results in scalability of operations. The wired Internet, for example, cannot be managed without hierarchical addressing and management. Essential services like routing are highly scalable owing to this hierarchical organization.

³clusterhead selection is done based on node degree [5]

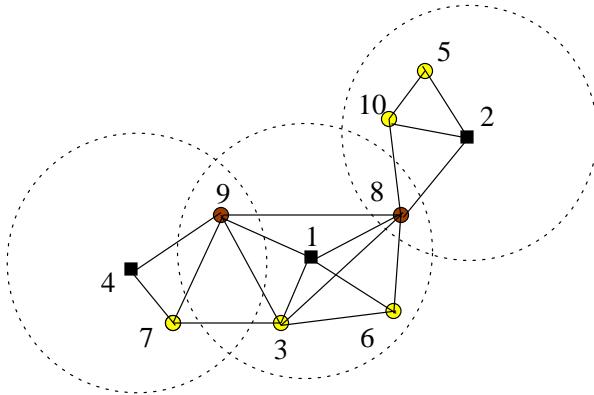


Figure 1: Lowest ID Clustering Algorithm

The notion of cluster-based organization in the context of mobile multihop wireless networks has been around for a long time. Ephremides et al. [4] introduced the idea through the concept of a distributed “linked cluster architecture”, which was mainly used for hierarchical routing, and for network adaptability to changes in connectivity. More recently, these ideas were revisited in the context of a mobile multihop multimedia wireless network (also known as a MANET) [5, 20].

Lowest-ID clustering is one of the most popular clustering schemes used in the old [4] as well as recent [5, 10] ad hoc networks literature. In [5], Gerla et al. propose a simple distributed clustering algorithm that yields clusters that are at most two hops in diameter. In each cluster, exactly one node, the one with the lowest ID among its neighbors, becomes a *clusterhead*, and maintains cluster-memberships of other member nodes.

The Lowest-ID algorithm proceeds as follows and results in the formation of clusters which are at most two hops in diameter:

- Each node is given a distinct ID and it periodically broadcasts the list of its neighbors (including itself).
- A node which only hears nodes with ID higher than itself is a “clusterhead” (CH).
- The Lowest-ID node that a node hears is its clusterhead, unless the Lowest-ID specifically gives up its role as a clusterhead (deferring to a yet lower ID node).
- A node which can hear two or more clusterheads is a “gateway”.
- Otherwise, a node is an ordinary node.

A cluster is identified by its clusterhead’s ID. Figure 1 shows a schematic of the result of using Lowest-ID clustering. There are 10 nodes with unique IDs (and with equal transmission radii) which form a connected graph. After the Lowest-ID clustering algorithm is executed, three clusters are

formed, as depicted by the three dotted circles. The dark squares at the centers of the respective circles are clusterhead nodes (1,2 and 4 in figure). The dark-colored circles which exist in the overlap regions between circles (8 and 9 in figure) are gateway nodes, and the light-colored circles are ordinary nodes.

In [5], an algorithm based on max-connectivity⁴ was also proposed, but it performed much worse than the Lowest-ID algorithm in terms of stability of clusters. The stability of clusters was measured by a metric, namely the average number of clusterhead changes per unit of time. We use the same metric for the evaluation of our algorithm too in Section 4.2.

In [3], the lowest-Id algorithm was improved by its variant LCC (Least Clusterhead Change) by imposing an additional rule on the clustering process: if a member ($\text{id} = i$) of cluster C moves within range of another cluster C' with higher ID, then do not perform reclustering unless i is the clusterhead of C . This helps in drastically reducing the number of changes in clusterheads due to reclustering. This approach too results in formation of clusters which are 2 hops in diameter and converges in $\mathcal{O}(d)$ time, where d is the diameter of the network. The clusterhead takes the responsibility of coordinating transmissions of packets and route discovery, and thus the network does not have to depend on classic flooding for routing.

Lowest-ID clustering was generalized to a *weight based* clustering technique, referred to as DCA (Distributed Clustering Algorithm) in [2]. In DCA, each node is assumed to have a unique weight (hence the weights are totally ordered) instead of just the node ID, and the clustering algorithm uses the weights instead of the IDs for the selection of clusterheads. However the technique of assignment of weights has not been discussed.

Clustering algorithms that generate clusters which may be greater than two hops in diameter have also been proposed in the literature [14, 20]. However, cluster maintenance is complicated and difficult in such situations, especially under high mobility, and can result in high overhead. We do not consider this class of algorithms in this paper.

2.2 Mobility Metrics

Several attempts have been made in the recent past to characterize mobility as an inherent phenomenon in a MANET [11, 9], and an attempt has been made to incorporate it into routing schemes [21]. However, little work has been done towards using mobility as the basis of clustering in ad hoc networks. In [11], a mobility metric has been proposed which is intended to capture and quantify the motion of nodes; the proposed metric is geometric in the sense that the speed of a node is measured relative to the other nodes. The mobility measure between any pair of nodes is defined

⁴A node with highest node degree becomes the clusterhead

as their absolute relative speed taken as an average over time. For determining the relative speed between any pair of nodes, a knowledge of the location coordinates is assumed for all nodes which might be available through a GPS⁵ like scheme. In order to arrive at the aggregate mobility metric for a particular scenario, the mobility measure is averaged over all pairs of nodes.

The above metric has certain deficiencies with respect to clustering: First, it assumes a GPS like scheme for calculation of relative speeds; in an ad hoc network especially in the indoors, we cannot assume the existence of GPS, and so we have to resort to other techniques for measuring relative mobility. Secondly, it fails to reflect in the true sense the movement of the nodes in the neighborhood of a particular node, since it is an aggregate measure taken over nodes in a given scenario. Actually the authors designed this metric for characterizing three different scenarios: a conference situation, a large event setting, and a disaster relief scenario. These scenarios were ranked in ascending order of their aggregate mobility metric.

Thus, a global mobility metric such as the one described above fails to capture the local mobility which is primarily responsible for cluster changes. At the same time the measurement of mobility between pairs of nodes that are far apart may not be relevant for local cluster formation. Hence, we focus on characterizing the local mobility of a nodes around a certain node in an efficient and online manner.

The mobility metric defined in [9] is not used as a basis for cluster formation. However, such a mobility metric can be useful for predictive mobility management. The authors of that paper propose a model for group mobility namely, the Reference Point Group Mobility Model (RPGM). In RPGM, each group has a logical “center” and the center’s motion defines the entire group’s motion behavior including location, speed, direction, acceleration etc. Usually the nodes are uniformly distributed within the scope of a group. The RPGM model defines the motion of groups explicitly by giving a motion path for each group. A path that a group will follow is given by defining a sequence of check points along the path corresponding to given time intervals.

An associativity based routing (ABR) protocol that uses mobility for routing has been proposed for mobile ad hoc networks [21]. ABR does not define a mobility metric but uses a *route stability* metric that is used by the routing protocol. In a MANET where mobile hosts (MHs) are acting as routers and where routes become stale by a MH’s movement, ABR employs a routing scheme where a route is selected based on nodes having associativity states that imply a period of stability.

A framework for dynamically organizing mobile nodes in ad hoc networks into clusters has been proposed in [16]. The focus of the authors in that work is on bounding the probability of path availability. A mobility model was developed and used to derive expressions for the probability of path availability as a function of time. The proposed mobility model is a random walk based model

⁵Geographic Positioning System

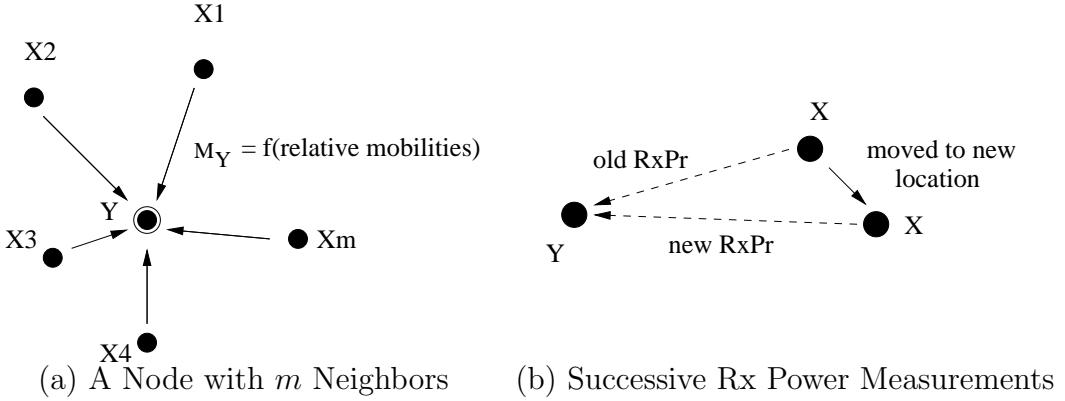


Figure 2: Aggregate Relative Mobility Calculation

which assumes that if the distance between two nodes is less than a system dependent threshold, then it is also possible to determine the conditional probability that the nodes will be within range of each other at time $t_0 + t$, given that they are located within range at time t_0 . However, we believe this probability based model fails to capture the real mobility of any node with respect to its neighbors and therefore it is not an adequate metric for clustering. Besides, it may be hard to implement such a complex algorithm on a bunch of low power nodes in a purely distributed manner.

We can see that none of the metrics described in this section are suitable for characterizing the relative mobility of nodes in a particular node's neighborhood in a MANET. Hence, we feel that there is a need to develop such a metric which can be used for clustering. In the next section, we describe a metric for capturing the mobility in a given node's local neighborhood, and then use it for stable cluster formation.

3 Mobility Based 2-Hop Clustering

In this section we describe our mobility metric and discuss how it can be used in formation of clusters which are at most 2 hops in diameter (like lowest ID). The lowest ID algorithm (even its LCC variant) does not couple the clustering process with the mobility of the nodes. If a node with a low ID happens to be highly mobile, it will cause severe reclustering to happen periodically when it moves into the transmission range of other clusterheads. In such occasions the lower ID node will prevail and reclustering will happen.

The basic idea in this paper is that the clustering process should be aware of the mobility of the individual nodes with respect to its neighboring nodes. A node should not be elected a clusterhead if it is highly mobile relative to its neighbors, since, in that situation, the probability that a cluster will break and that reclustering will happen is high. Instead, we should attempt to select a node that is less mobile relative to its neighbors for the role of a clusterhead.

The mobility metric proposed in this paper does not assume the availability of any absolute location information (e.g. GPS) at a node. It also does not assume availability of velocity information at every node. In the next two subsections, we describe our mobility metric and how the clustering algorithm uses it for formation of stable clusters.

3.1 An Aggregate Local Mobility Metric

In our solution, in order to model mobility, we purport that the power level (received signal strength) detected at the receiving node, $RxPr$, is indicative of the distance between the transmitting and receiving node pairs. In the ideal situation, Friis' free space propagation model is used, which uses an inverse-square dependence of the ratio of received and transmit power on the physical distance between the transmitter and the receiver, i.e. $\frac{RxPr}{TxPr} \propto \frac{1}{d^2}$ [6]. But in real life, an exact calculation of the distance between a transmitter and a receiver may not be possible from the measured signal strengths owing to the complexities involved in accurate channel modeling. However, from the ratio of $RxPr$ between two successive packet transmissions (periodic "hello" messages) from a neighboring node, we can get good knowledge about the relative mobility between the two nodes⁶. Hence, we define the relative mobility metric, $M_Y^{rel}(X)$, at a node Y with respect to X , in this manner:

$$M_Y^{rel}(X) = 10 \log_{10} \frac{RxPr_{X \rightarrow Y}^{new}}{RxPr_{X \rightarrow Y}^{old}} \quad (1)$$

If $RxPr_{X \rightarrow Y}^{new} < RxPr_{X \rightarrow Y}^{old}$, then $M_Y^{rel}(X) < 0$, and a negative value of the relative mobility metric between any two nodes will indicate that the two nodes are moving away with respect to each other. On the other hand if $RxPr_{X \rightarrow Y}^{new} > RxPr_{X \rightarrow Y}^{old}$, then M_Y^{rel} is positive (subscripts have been omitted in order to reduce clutter), and that indicates that the nodes are moving closer to each other. For a node with m neighbors, there will exist m such values for M_Y^{rel} . This situation is depicted in Figure 2.

We calculate the aggregate local mobility value M_Y at any node Y by calculating the *variance* (with respect to zero) of the entire set of relative mobility values $M_Y^{rel}(X_i)$, where X_i is a neighbor of Y .

$$\begin{aligned} M_Y &= var_0(M_Y^{rel}(X_1), M_Y^{rel}(X_2), \dots, M_Y^{rel}(X_m)) \\ &= E[(M_Y^{rel})^2] \end{aligned} \quad (2)$$

Here, var_0 denotes the variance with respect to zero (and not the mean of the sample) and is equal to $E[(M_Y^{rel})^2]$ which is the expected value of the squares of the m relative mobility samples from Y 's neighbors.

⁶We do not consider the effects of multipath, small-scale and large-scale fading in this study.

In this manner, any node Y which also acts as a receiver measures the power levels in successive transmissions from all its neighbors and a variance of these values (with respect to zero) is a representative value for the aggregate relative mobility metric M_Y for that node. The main rationale behind calculating the variance of the relative mobility values with respect to each neighbor is that a low value of M_Y indicates that Y is relatively less mobile with respect to its neighbors. On the contrary, a high value of M_Y indicates that Y is highly mobile with respect to its neighboring nodes. As we have mentioned before, we should favor the nodes that have a low variance in relative mobilities with respect to its neighbors, for becoming clusterheads.

We believe that the variation in received signal power is a better indicator of mobility than pure distance or speed owing to environmental characteristics. For example, the communication between two nearby cars on a street with dense foliage is more likely to suffer from high attenuation of signal strength than that between two cars that are farther away on a clear road. In reasonably short time scales (a few seconds), the surrounding environment is unlikely to change by a great deal, so the variation in received signal strength is a good index of local mobility.

The calculation of this mobility metric is a simple task that can be achieved in a distributed manner, and the measurement of the incoming signal strength is easily possible with existing hardware. Note that we only consider transmissions that are successfully received by the MAC layer.

Since the calculation of the relative mobility metric $M_Y^{rel}(X)$ needs two successive packet transmissions, we require that the time interval after which the aggregate mobility metric M_Y is calculated at Y should include two successive “hello” message transmissions from all Y ’s neighbors. It is possible that during that time interval, certain nodes move out of/come into range of node Y . We use a heuristic to tackle this problem: nodes which do not participate in two successive transmissions to node Y are excluded from the calculation. Thus, only those nodes which have been in the neighborhood of Y for that particular time interval are considered for the mobility metric calculation. This calculation is performed at every node, and thus, each node will maintain an aggregate relative mobility metric.

We intuitively expect that on average, M_Y would perform as a better metric if Y has more neighboring nodes with mobilities in a given range. Although for sparsely connected topologies and/or low transmission radii, the aggregate mobility calculation can be imprecise, we argue that this yields a better picture of the aggregate behavior of nodes in the local neighborhood of Y in moderately to highly dense topologies. In Section 4.2, we will demonstrate that this is indeed the case.

3.2 MOBIC - A Lowest Relative Mobility Clustering Algorithm

In order to use the mobility metric presented in the previous section for clustering, we propose a distributed, lowest mobility clustering algorithm, MOBIC, which is similar in execution to the Lowest-ID algorithm as described in Section 2.1, except that the mobility metric is used as a basis of cluster formation instead of the ID information. We describe our algorithm in the following steps:

- All nodes send and receive “Hello” messages to/from their neighbors. Each node measures the received power levels of two successive “Hello” message transmissions from every neighbor, and then calculates the pairwise relative mobility metrics using (1). Before sending the next broadcast packet to its neighbors, a node computes the aggregate relative mobility metric M using (2). M is represented by a double precision floating point number.
- All nodes start in Cluster_Undecided state. Every node broadcasts its own mobility metric, M (initialized to 0 at the beginning of operations) in a “Hello” or “I’m Alive” message to its 1-hop neighbors every Broadcast_Interval (BI) period. It is then stored in the neighbor table of each neighbor along with a timeout period (TP) set. This algorithm is executed in a distributed manner. Thus, a node receives the aggregate mobility values from its neighboring nodes, and then compares its own mobility value with those of its neighbors.
- If a node has the lowest value of M (aggregate relative mobility) amongst all its neighbors, it assumes the status of a Cluster_Head; otherwise it declares itself to be a Cluster_Member. This algorithm leads to the formation of clusters which are at most two hops in diameter. If a node is a neighbor of two clusterheads, then it becomes a “gateway” node. If two neighboring nodes in a Cluster_Undecided state have the same value of M , we resort to comparison of IDs and follow the Lowest-ID algorithm.
- In case where the mobility metric of two clusterhead nodes is the same, and they are in contention for retaining the Cluster_Head status, then the selection of the clusterhead is based on the Lowest-ID algorithm wherein the node with the lowest ID gets the status of the Cluster_Head. If a node with Cluster_Member status with a low mobility moves into the range of another Cluster_Head node with higher mobility, reclustering is not triggered (similar to LCC [3]).
- In a mobile scenario, if two nodes with status Cluster_Head move into each other’s range, reclustering is deferred for Cluster_Contention_Interval (CCI) to allow for incidental contacts between passing nodes. If the nodes are in transmission range of each other even after the CCI timer has expired, reclustering is triggered, and the node with the lower mobility metric assumes the status of Cluster_Head.

Table 1: Simulation Parameters

Parameter	Meaning	Value
N	Number of Nodes	50
$m \times n$	Size of the scenario	$670^2, 1000^2 \text{ m}^2$
$MaxSpeed$	Maximum Speed	1, 20, 30 m/sec
Tx	Transmission Range	10 – 250 m
PT	Pause Times	0, 30 sec
BI	Broadcast Interval	2.0 sec
TP	Timeout Period	3.0 sec
CCI	Cluster Contention Interval	4.0 sec
S	Simulation Time	900 sec

Theorem 1 *MOBIC yields clusters of diameter ≤ 2 hops, and no two clusterheads are in range of each other.*

Proof: It has been shown in [2] that for a *totally ordered* weight distribution, a distributed algorithm similar to Lowest-ID yields clusters which satisfy the above properties. In our case, however, the weights (Aggregate Local Mobility Metric) may not be totally ordered and may be changing dynamically.

If all nodes have different values of aggregate local mobility (M), then the weights (mobility metric) will be totally ordered and MOBIC will result in clusters which obey the above properties. This situation is likely to happen most often since the nodes are mobile and the variance of relative mobilities is being calculated using double precision arithmetic in every node's local neighborhood.

However, if a few nodes within the transmission range of each other have the same value of M , then the weight function will be modified from M to $\{M, ID\}$. Therefore, the *augmented* weights will be totally ordered and the clustering process will generate clusters of diameters at most two hops. If two or more clusterheads happen to come within range of each other, then the one with the lowest weight retains the role of the clusterhead. Hence, no two clusterheads will be neighbors in a stable state. \diamond

A cluster-based routing protocol like CBRP [10] that runs on top of the Lowest-ID scheme can also run on top of MOBIC with minimum changes. We have simulated both MOBIC and Lowest-ID using the *ns-2* network simulator, and have presented a comparative analysis in Section 4.2.

In this paper, we have not presented the performance analysis of any routing protocol that can run on top of MOBIC, but we feel that more stable cluster formation can directly result in significant improvement of performance.

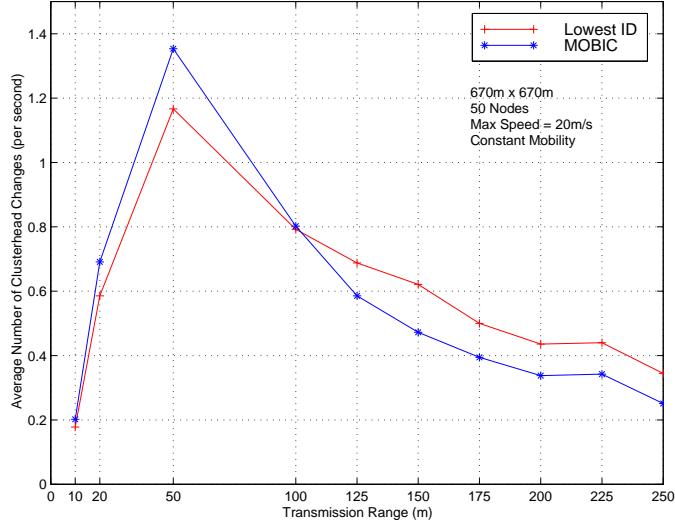


Figure 3: Number of CH Changes: Lowest-ID vs. MOBIC

4 Results and Discussion

4.1 Simulation Environment and Parameters

The simulations were performed using the *ns* network simulator from UC Berkeley [17] with wireless extensions from CMU [18]. The scenarios were randomly generated with input parameters such as maximum speed, pause times, number of nodes, area etc. We implemented MOBIC using the aggregate relative mobility metric that we proposed in Section 3.1. The details of the algorithm have been provided in Section 3.2. The simulation parameters have been listed in Table 1. We have compared the performance of MOBIC with the Lowest-ID algorithm with respect to a cluster stability metric CS , which denotes the number of clusterhead changes in a given time period.

The aggregate mobility values (M) were stamped onto each “hello” broadcast packet and sent by the sender node to its neighbors. The receiver nodes in *ns* receive the packets and extract both the aggregate mobility information (from the data part of the packet) as well as the $RxPr$ of the current packet (from the MAC layer). The relative mobility is calculated from two successive $RxPr$ values as described in Section 3.1. Then the M values are calculated by using (2) and stamped onto the next broadcast packet. Once the M values of all neighbors are known, the clustering process is executed. The byte overhead of the “hello” packets is increased by 8 bytes only⁷.

⁷size of a double precision number

4.2 Discussion of Results

Figure 3 shows the comparison between the performance of Lowest-ID and MOBIC for a reasonably mobile scenario with $MaxSpeed = 20 \text{ m/s}$ and $PT = 0 \text{ sec}$, i.e. constant mobility.

We note that for both Lowest-ID and MOBIC, the number of clusterhead changes first increases with the increase in transmission range and then decreases. For small transmission ranges ($Tx \sim 10$), most nodes remain out of each other's range; there are severe disconnections in the topology and therefore, there are fewer changes in the status of nodes.

As Tx increases, more nodes will appear within transmission ranges of each other for short periods of time. This results in clusterheads giving up their roles to other nodes (by lowest id and mobility measurements in Lowest-ID and MOBIC, respectively), and hence the number of clusterhead changes increases rapidly. However, for transmission ranges greater than 50 m , more nodes are within range of other nodes for longer periods of time. Therefore, less number of clusters, which are larger in size, are formed, and mobility of nodes does not cause them to frequently move in and out of range of each other. Hence, the number of clusterhead changes decreases.

It is evident from Figure 3 that for moderate/high transmission ranges ($> 100 \text{ m}$), MOBIC outperforms the Lowest-ID clustering algorithm. In fact, beyond a transmission range of 125 m , the reduction in the number of clusterhead changes is by about 100, and for $Tx = 250 \text{ m}$, MOBIC yields a gain of close to 33% over Lowest-ID clustering. These large gains due to MOBIC over Lowest-ID clustering (as depicted in Figure 3) can be directly attributed to the following fact: in MOBIC, nodes with the lowest relative mobility in a neighborhood get chosen as clusterheads, the probability that they will change clusters frequently is lower as compared to the clusterheads in the Lowest-ID case.

Although MOBIC does not perform as well as Lowest-ID for lower values of $Tx \sim 50$ (since clusters are broken up frequently, and the neighbor-set is changing frequently resulting in less accurate calculations of the aggregate mobility metric M), it does outperform the latter for medium to high values of Tx where the clusters are larger in size. As expected, our aggregate mobility metric performs better if a node has more neighbors.

Figure 4 shows the variation in the number of clusters that are formed as a result of executing both clustering algorithms. The number of clusters strictly decreases with increase in transmission range. This is in accordance with our expectation since the nodes are uniformly distributed, and increase in the transmission radius results in more nodes under the jurisdiction of a clusterhead, and hence a less number of clusters. However, as Tx increases even further ($> 125 \text{ m}$), the rate of reduction in number of clusters decreases due to the increase in overlap between adjacent clusters, and this results in an increase in the number of nodes belonging to multiple clusters.

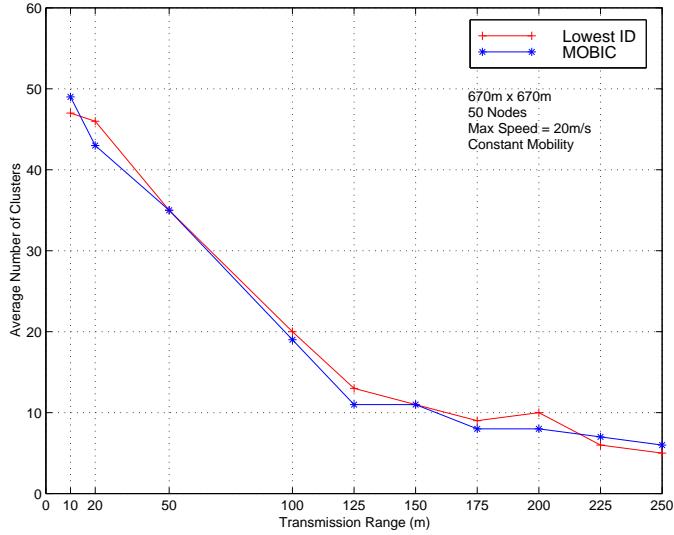


Figure 4: Number of Clusters: Lowest-ID vs. MOBIC

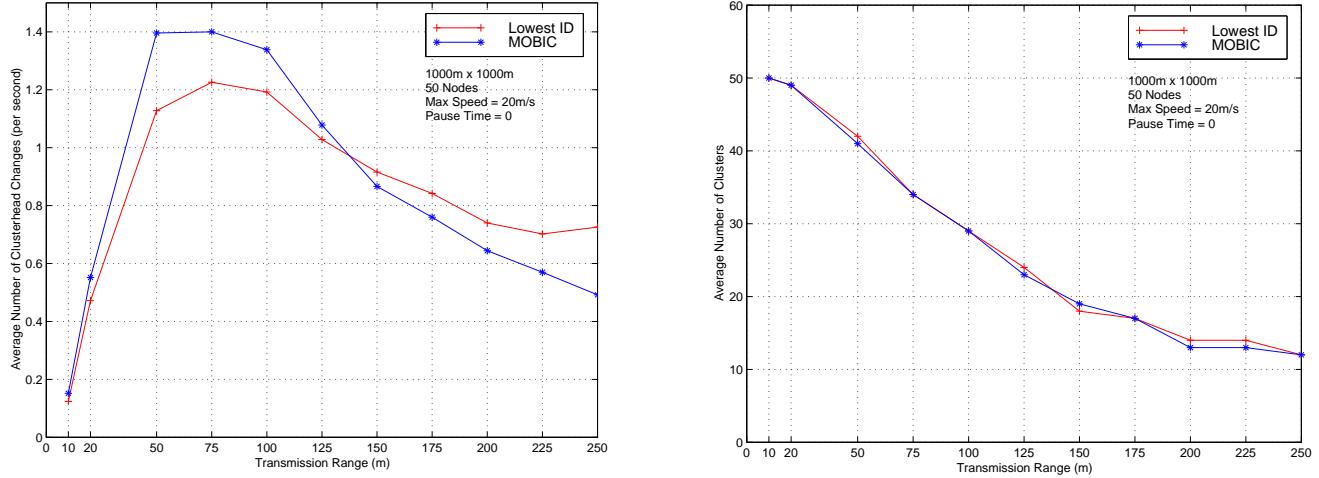


Figure 5: Lowest-ID vs. MOBIC in a Larger Area

Another observation that we can make from Figure 4 is that there is little difference between Lowest-ID and MOBIC with respect to the number of clusters metric. This is because both operate on similar random movement patterns and fundamentally both are variations of a “local” weight based clustering technique.

4.3 Effect of Area Density of Nodes

Next, we explore the effect of area density of nodes on the cluster stability metric. We simulated both techniques on a scenario ($1000m \times 1000m$) with a larger area while keeping the other parameters (average mobility patterns etc.) the same. In this case, the nodes are more sparsely distributed than in the case presented in Section 4.2. Therefore, there are more clusterhead changes in the current situation (see Figure 5).

Another observation is that the peak of the curve has shifted towards the right in this case as compared to the $670m \times 670m$ case. This can be attributed to the fact that uniformly distributing the same number of nodes in a larger area results in the nodes being farther apart from each other on average, and this means that a larger transmission radius is required to span the neighboring nodes, the situation when the clusterhead changes start to diminish.

We can also see from Figure 5 that the transmission radius at which MOBIC starts to outperform Lowest-ID is greater than the one in the previous case ($670m \times 670m$). That is because a larger radius is required to include the same number of neighbors that were deemed appropriate in the previous case for good aggregate mobility characterization by the method described in Section 3.1. It is for transmission ranges greater than this value that the mobility metric is able to capture the local aggregate mobility and use it well for clustering. Since the nominal transmission radii for radios used in such large open areas are usually in the range of $150 - 250$ meters, MOBIC will outperform Lowest-ID for these ranges.

A couple of more observations are noteworthy in Figures 3, 4, and 5. For the 670×670 case, the number of clusterhead changes is maximum for a transmission radius, $Tx \approx 50m$, and the number of clusters is approximately 35; and for the 1000×1000 case, the maximum is achieved at $Tx \approx 75m$ and the number of clusters is approximately the same as before. We see that for a constant number of nodes ($N = 50$) if the areas are related by a factor of $f = \frac{1000 \times 1000}{670 \times 670} \approx 2.22$ we get the same number of clusters if the transmission radii are related by a factor of $\frac{75}{50} = 1.49 \approx \sqrt{f}$.

Our tentative explanation for this phenomena is the following: suppose that $A_{ov}(Tx, m)$ is the total overlap area between clusters for the $m \times m$ region at the critical Tx , and $A(Tx, m)$ is the total area occupied by all clusters. The latter is proportional to m^2 under uniform distribution of nodes. Let C be the number of clusters. Now, $A = C\pi Tx^2 - A_{ov}$ which implies, $\frac{A_{ov}}{A} = \frac{C\pi Tx^2}{A} - 1$. Our claim is that if the bounding area is scaled f times and the number of nodes is kept constant (i.e., the node density changes), the maxima in clusterhead changes occurs when $\frac{A_{ov}}{A}$ is in a critical range (i.e., it is not too low so that the clusters are mostly disconnected, neither is it high enough for stable formation of clusters), and that is same for both scales. We see that C remains the same and the Tx 's have to be scaled by \sqrt{f} to keep $\frac{A_{ov}}{A}$ constant.

We make a similar observation regarding the value of the transmission range where MOBIC outperforms Lowest-ID. For the 670×670 case, this happens at $Tx \approx 100m$, and the number of clusters is approximately 20; on the other hand, for the 1000×1000 case, MOBIC outperforms Lowest-ID at $Tx \approx 140m$, and the number of clusters is approximately the same (~ 20). Again the transmission radii are approximately related by a factor $1.4 \approx \sqrt{f}$. We do not have an analytical model for this scenario. However, our tentative explanation for this phenomena is the following: MOBIC starts performing better than Lowest-ID when there are a critical number of neighboring nodes around a clusterhead node. That critical number can be achieved by scaling the area covered

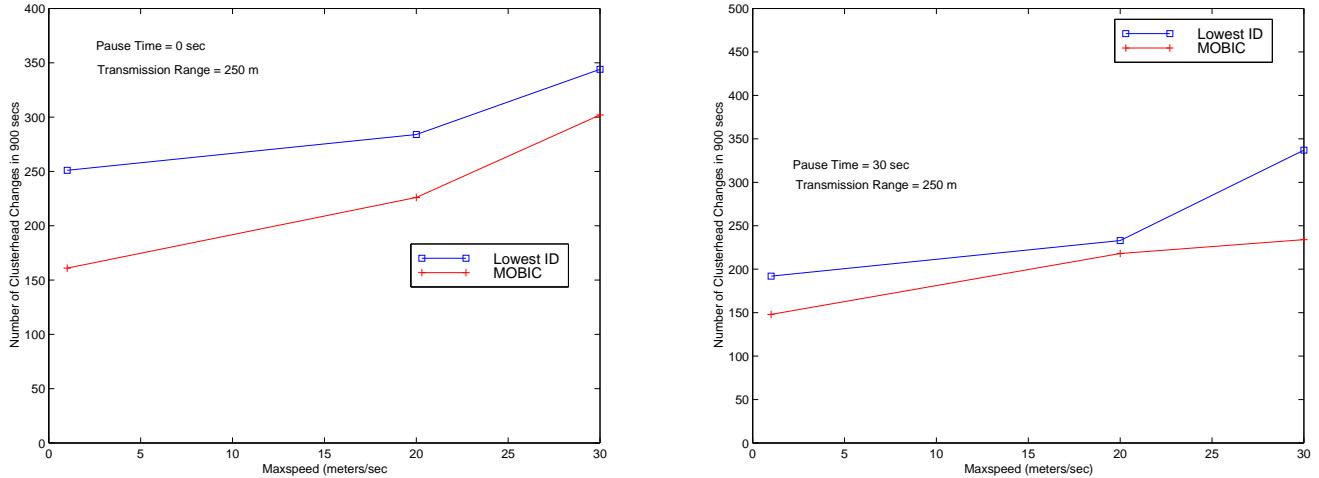


Figure 6: Effect of Varying Speeds

by the transmission range of a node by the same factor f and thus by scaling Tx by \sqrt{f} .

Exact correlation between the performance of clustering algorithms and the parameters such as area, number of nodes, transmission radius, mobility speeds etc. can only be achieved by developing an analytical model which will be a subject of future research.

4.4 Variation in Degree of Mobility

Figure 6 shows the effect of varying mobility on the performance of MOBIC with respect to Lowest ID. In Figure 6(a), we can see that for $Tx = 250$ (a typical transmission range used in previous simulation experiments conducted elsewhere [11]), and for the “always mobile” case ($PT = 0$), MOBIC outperforms Lowest-ID by 50 – 100 clusterhead changes.

Even for highly mobile situations ($MaxSpeed = 30 \text{ m/s}$), MOBIC yields an appreciable gain over Lowest-ID owing to its capability of adapting itself to the mobility of nodes. Expectedly, the gains are slightly reduced for less mobile scenarios (with $PT = 30 \text{ sec}$); but upon increasing the speed, we observe that MOBIC manages to maintain its gains.

From the above results, we can easily conclude that MOBIC is highly suitable for stable cluster formation in situations involving both low and high mobility. Since it is based on a relative mobility measure in the neighborhood of every node, it adapts well to varying levels of mobility.

5 Future Work

This paper is a part of our larger ongoing efforts in the area of Mobile Ad Hoc networks. Integrating a mobility metric into clustering is the first step in this direction. Our future efforts will address

the following issues:

We plan to integrate the mobility metric with a cluster based routing protocol. This will not only affect clustering (as we have shown in this paper) but will also affect the update intervals between the “Hello” messages. Such a mobility adaptive cluster-based routing protocol will improve the performance of the network under different levels of mobility.

The aggregate mobility metric that was introduced in this paper was computed by calculating the variance of relative mobilities between a node and all its neighbors over a small time period. It is possible that keeping some history information about the mobility values may yield more stable metrics and can result in more stable clusters.

It is envisaged that the mobility metric will yield better results when mapped to specific scenarios where the relative mobility between nodes does not differ significantly. Examples include cars traveling on a highway or attendees in a conference hall. We plan to study the performance of the mobility based clustering in these specialized scenarios.

6 Conclusions

Clustering is an important technique for imposing hierarchy and organization in a mobile ad hoc network. It helps in reducing the complexity in management of information about the mobile nodes, and therefore simplifies some essential processes such as routing and bandwidth allocation. Mobility of nodes causes clusters to get disrupted and thus triggers reclustering. Therefore, the use of mobility information for cluster formation is a reasonable proposition. In this paper, we presented a new mobility metric for nodes in a MANET. It is simple to measure and does not assume any knowledge of absolute location.

We proposed a weight based clustering algorithm, MOBIC, which uses the proposed mobility metric for formation of clusters that are at most two hops in diameter. Using ns-2 simulations, we have demonstrated that the gains due to MOBIC are significant as compared to those of the Lowest-ID algorithm. (MOBIC outperforms Lowest-ID by as much as 33% in number of clusterhead changes) Therefore, we conclude that relative mobility is a better criterion for clustering the nodes rather than plain IDs which are not representative of node mobility in a mobile ad hoc network.

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