A Model of Autonomous Motion in Ad Hoc Networks to Maximise Area Coverage

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***Abstract*—Ad hoc networks are self-configuring networks of mobile nodes, connected by wireless links. Suppose each mobile node can make observations within a circular area of radius r_{obs} centred on its own location. The area coverage of the network is defined as the total area observed by the mobile nodes. We investigate a distributed scalable method based on local interactions with minimal sensing and low computational cost whereby the nodes move autonomously (self-deployment) in order to maximise the coverage of the network, while at the same time ensuring that the mobile nodes do not move so far away from each other (thus trivially maximising the coverage) that they become disconnected. Certain nodes may be instructed to move to specified locations. These guide nodes induce a correlated movement of groups of nodes which follow the guide nodes and establish maximal coverage in the specified locations. Simulation results demonstrate the coverage achieved by a group of 100 nodes when moving on an unbounded plane (optional guide nodes induce a collective motion to areas of interest) and when moving on a bounded plane with barriers or hills.**

***Index Terms*—Area coverage; biologically inspired motion rules; autonomous motion; behavioural zones; collective motion; distributed control; mobile ad hoc networks; mobility models; self-deployment; self-organization.**

I. Introduction

Collective motion often arises in mobile ad hoc networks (MANETs) and often involves communications among and between clusters of nodes who coordinate their movements in order to achieve intra- and inter-cluster goals.

Many movement models [1, 5, 6, 7, 8, 10, 11, 12] have been developed in order to analyse and evaluate the efficiency of MANET protocols and services. In this paper we investigate a distributable scalable method based on local interactions with minimal sensing and low computational cost which enable nodes in an ad hoc network to spatially distribute themselves so as to maximize their area coverage.

Collective motion can be modelled by the application of a system of local rules derived from an *artificial biology* which gives rise to node movements which mimic animal swarming, flocking or schooling behaviour [2, 3, 14]. These models define a system of concentric behavioural zones. Depending on the position of an animal relative to other herd members, and the occupancies of the zones, the animal will either align its direction and velocity to that of its neighbours or approach or depart their vicinity. Mathematical analysis of the behaviour of such herds [15, 16] shows that the movement patterns can maintain herd cohesion.

We present a model of collective motion using movement rules which are based on a Lagrangian self-organising model of general movement that was used to investigate the spatial dynamics of animal groups [2, 3]. Each mobile node decides about its own movement according to local decision rules which take into account local information such as the positions of the neighbours, but not the state of the network as whole.

The paper is organised as follows. Section II presents a model that describes the motions of mobile nodes. Section III presents the results of simulation experiments to compute the emerging spatial distributions. The impact of the spatial distribution of the nodes on the efficient transmission of data is presented in Section IV. The conclusions are presented in Section V. The electronic version [9] of this paper contains links to files which, when loaded, play animations using the default video player and the Xvid4 codec. The animations show several emerging spatial distributions as the nodes move to maximize their area coverage.

II. A biologically-inspired movement model

A. Spatial sorting in animal groups

Consider a set of nodes located on a 2D plane (3D motions are considered in [2]: the motion rules in 2D and 3D are essentially the same). Define three concentric circular zones centred on node i namely a zone of repulsion (ZoR), a zone of orientation (ZoO) and a zone of attraction (ZoA) with radii $0 < r_r < r_o < r_a \le r_d$ respectively where r_d denotes the maximum radio transmission distance between nodes.

Let $\mathcal{N}_i^r$ denote the set of nodes that are at most r_r units distant from node i. Let $\mathcal{N}_i^o$ denote the set of nodes that are more than r_r but at most r_o units distant from node i. Let $\mathcal{N}_i^a$ denote the set of nodes that are more than r_o but at most r_a units distant from node i. Note that $i \notin \mathcal{N}_i^r \cup \mathcal{N}_i^o \cup \mathcal{N}_i^a$. Let $N_i^r = |\mathcal{N}_i^r|, N_i^o = |\mathcal{N}_i^o|$ and $N_i^a = |\mathcal{N}_i^a|$.

Rule 1. If nodes are present in the ZoR then node i moves away from these nodes in the direction

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$$\mathbf{v}_i(t+\Delta) = -\sum_{n\in\mathcal{N}_i^r} \frac{\mathbf{r}_n(t)-\mathbf{r}_i(t)}{|\mathbf{r}_n(t)-\mathbf{r}_i(t)|}. \quad (1)$$

Rule 2. If there are no nodes in the ZoR, but nodes are present in the ZoO or the ZoA then node i moves towards these nodes in the direction

$$\mathbf{v}_i(t+\Delta) = \frac{N_i^o \mathbf{v}_i^o(t+\Delta) + N_i^a \mathbf{v}_i^a(t+\Delta)}{N_i^o + N_i^a}$$

that represents a weighted average between aligning the movement vector of node i to the movement vectors of the nodes in the ZoO

$$\mathbf{v}_i^o(t+\Delta) = \sum_{n\in\mathcal{N}_i^o} \frac{\mathbf{v}_n(t+\Delta)}{|\mathbf{v}_n(t+\Delta)|}$$

and the movement vectors of the nodes in the ZoA

$$\mathbf{v}_i^a(t+\Delta) = \sum_{n\in\mathcal{N}_i^a} \frac{\mathbf{r}_n(t)-\mathbf{r}_i(t)}{|\mathbf{r}_n(t)-\mathbf{r}_i(t)|}.$$

Note that the direction of movement $\mathbf{v}_i(t+\Delta)$ of node i depends on the $\mathbf{v}_n(t+\Delta)$ of other nodes $n \neq i$ which, depending on the order of the evaluation of the movement directions of the nodes, may not have been determined yet. We therefore assume that, for the purpose of calculating $\mathbf{v}_i(t+\Delta)$, if the value of $\mathbf{v}_n(t+\Delta)$ has not yet been computed, then we use $\mathbf{v}_n(t+\Delta) = \mathbf{v}_n(t)$. The directions $\mathbf{v}_i(t+\Delta)$ are evaluated in random order.

Rule 3. If there are no nodes in the ZoR, the ZoO, or the ZoA, then node i does not change its current movement

$$\mathbf{v}_i(t+\Delta) = \mathbf{v}_i(t).$$

B. Spatial sorting adapted for mobile nodes

The movement model [2] was adapted to better describe the motion of mobile nodes pursuing the four goals of coverage, convergence, efficiency and collective motion.

Coverage. The movement model [2] did not consider boundary effects where the motions of the nodes are constrained by barriers. For example, a pattern consisting of an odd number of irregularly spaced co-linear nodes may arise when nodes encounter a barrier. The movement model [2] preserves this pattern. This is resolved by assigning weights inversely proportional to the distance between the nodes, which encourages nearby nodes in the ZoR to move away from each other. The nodes will therefore become more evenly distributed, especially at the boundaries of a confined area where movement is limited.

Convergence. Nodes should become stationary when near-optimal coverage is achieved. However, the movement model [2] triggers further movements giving rise to an oscillating motion. The movement model was therefore modified so that a node stops moving when it has aligned itself with its neighbours in the ZoO. In this case the node is at the desired distance from its neighbours: it is neither too close to its neighbours in which case there would be a large overlap between its area of observation and the areas of observation of its neighbours, nor is it too far away so that there would be a risk of losing connectivity with some of its neighbours.

Efficiency. The movement rules must be simple so that they place minimal computational and data sensing demands on the mobile nodes. The movement model [2] was therefore changed so that movement decisions are based only on the *positions* of the nodes in the three zones. It is no longer necessary to know the movement speeds and movement directions of the nodes in the three zones, or to approximate these values by comparing their present and past locations. Note that rule 0 below, although formulated in terms of movement directions, is computed using node positions only.

Collective motion. A node is either a *guide* node or a *standard* node. A node is a standard node unless stated otherwise. A guide node may be instructed to move to a specified location. In this case, the guide node must induce a collective notion among its neighbouring nodes so that the nodes follow the guide node to the vicinity of the specified location and establish maximal coverage in this vicinity.

The collective motion is accomplished by adding a new rule of the highest priority which moves the nodes towards the guide node or, if there is more than one guide node, towards the nearest guide node. The component of the movement in the direction of the guide node is relatively small, otherwise the emerging spatial distribution would be lost in favour of all the nodes clustering close to a guide node.

Measurement errors. The distance $\mathbf{r}_n(t) - \mathbf{r}_i(t) = (x, y)$ between nodes n and i at time t is computed as $x = x + E(0.05x)\cos\theta$ and $y = y + E(0.05y)\sin\theta$ where $E(z)$ is a random variable sampled from an exponential distribution with parameter z and θ is a RV sampled from a uniform distribution in the range $[-\pi, \pi]$.

Let $\mathbf{v}_i(t)$ denote the movement direction of node i during the interval $[t, t+\Delta)$ and let $\mathbf{r}_i(t)$ denote the position of node i at time t. Since the movement speed v_s is assumed to be constant, is completely determined by assigning a (not necessarily normalised) direction $\mathbf{v}_i(t)$.

Rule 0. If a guide node T is present in any of the three zones, then node $i \neq T$ moves in the direction

$$\mathbf{v}_i^*(t+\Delta) = \frac{\lambda_i \mathbf{v}_i(t+\Delta) + \lambda_T \mathbf{v}_i^T(t+\Delta)}{\lambda_i + \lambda_T}$$

where $\lambda_i = 10$, $\lambda_T = 1$, $\mathbf{v}_i(t+\Delta)$ denotes the movement direction derived from Rules 1, 2 and 3 and $\mathbf{v}_i^T(t+\Delta)$ represents the normalised direction of the nearest guide node T

$$\mathbf{v}_i^T(t+\Delta) = \frac{\mathbf{r}_T(t)-\mathbf{r}_i(t)}{|\mathbf{r}_T(t)-\mathbf{r}_i(t)|}.$$

If no guide node is present in any of the three zones, then node i moves in the direction as determined by Rules 1 through 3.

Rule 1. If nodes are present in the ZoR then node i moves away from these nodes in the direction

$$\mathbf{v}_i(t+\Delta) = -\sum_{n\in\mathcal{N}_i^r} \mu_n(i) \frac{\mathbf{r}_n(t)-\mathbf{r}_i(t)}{|\mathbf{r}_n(t)-\mathbf{r}_i(t)|}$$

where the weight $\mu_n(i) = 1/\max(|\mathbf{r}_n(t) - \mathbf{r}_i(t)|^2, 0.05m)$.

Rule 2. If there are no nodes in the ZoR but nodes are present in the ZoO then node i does not move so that

$$\mathbf{v}_i(t + \Delta) = \mathbf{0}.$$

If there are no nodes in the ZoR and the ZoO, but nodes are present in the ZoA then node i moves towards these nodes in the direction

$$\mathbf{v}_i(t + \Delta) = \sum_{n \in \mathcal{N}_i^a} \frac{\mathbf{r}_n(t) - \mathbf{r}_i(t)}{|\mathbf{r}_n(t) - \mathbf{r}_i(t)|}.$$

Rule 3. If there are no nodes in the ZoR, the ZoO and the ZoA, then node i does not move so that $\mathbf{v}_i(t + \Delta) = \mathbf{0}$. Note that node i is not necessarily permanently immobilised since the sets $\mathcal{N}_r$, $\mathcal{N}_o$ and $\mathcal{N}_a$ may change.

C. Maintaining cluster connectivity

The set of mobile nodes may separate into distinct clusters each following a different guide node. In order to maintain wireless connectivity between the clusters, some nodes may leave their clusters to form a trail of transit nodes connecting the separated clusters. Such transit nodes must be no further than r_d apart, else they would lose connectivity with each other. These transit nodes must also not be too close together, else too many nodes would be acting as relays between the clusters and wasting their capacity for area observation far away from the vicinity of the guide nodes where observations have to be made.

For this purpose, the following heuristic is used. Before executing a movement step, every node k determines if within a radius r_d there is one or more nodes n which, if the movement step was executed, would be located at a distance further than r_d from node k. Executing this movement would result in node k losing radio contact with node n unless another node r can be used as a relay between node k and node n: such a node r must be no more than r_d distant from nodes k and n. If such a relay node r cannot be found, then node k is immobilised and connectivity with node n is preserved. Likewise, for reasons of symmetry, node n cannot move further away from node k.

III. Simulation Experiments

We developed a simulator in Java using the DESMO-J simulation framework [13]. The simulation model computes the evolution of the spatial distribution of the nodes according to the rules presented in Section II.The simulation is run for up to 40,000 time units. The node movements are updated every $\Delta = 0.1$ time units. The simulation parameters are given in Table I.

A. Coverage on a 2D surface with distant boundaries

The first two experiments investigate the coverage attained by the nodes when the movements of the nodes are not restricted by boundaries and barriers. In this case no obstacles prevent the nodes from leaving each other's ZoR. Fig. 1 shows the final spatial distribution of the 100 nodes when the nodes are initially uniformly located in a $10\,m \times 10\,m$ area at the centre of a $150\,m \times 150\,m$ plane. The nodes are indicated by • symbols. Nodes that are at the desired distance D from each other are connected by gray lines. Nodes that are too close to each other (separated by a distance less that $0.8D$) are connected by blue lines. Most of the nodes are able to locate themselves approximately $12.5\,m$ apart at the vertices of a hexagonal lattice.

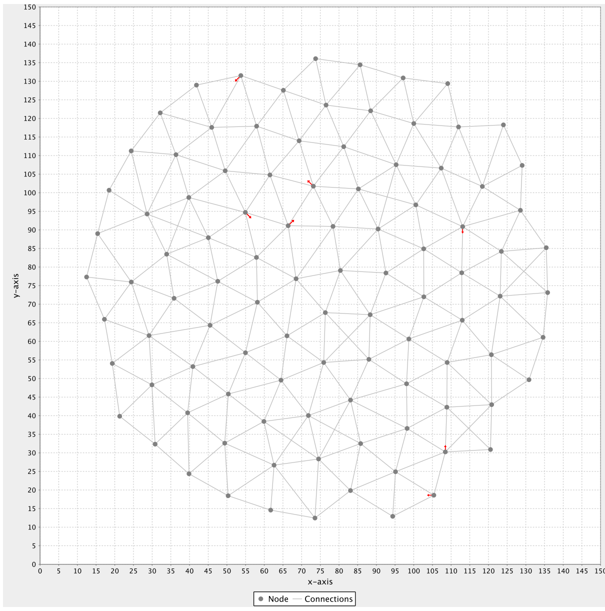

Fig. 1. The coverage achieved when 100 nodes are originally located in the central $10\,m \times 10\,m$ of a $150\,m \times 150\,m$ plane.

The lattice quality can be measured as follows. Measure the angle between two randomly chosen proximate nodes (proximate nodes are no further than $1.2D$ apart) as observed from a third proximate node. For an hexagonal lattice, the angle should be close to a multiple of $60°$. Define the error to be the absolute value of the difference between the angle and the closest multiple of $60°$. The error lies in the range $(0°, 30°)$ and the quality of the lattice is given by the average value of the error over all pairs of nodes. Each simulation was replicated 40 times. The model yields an average angle error of $11.2° \pm 0.9°$. If the ZoR/ZoO/ZoA radii are altered to 13/13/26 then the average angle error is $6.4° \pm 2.2°$.

Fig. 2 shows the final spatial distribution of the 100 nodes when guide nodes are used to induce a collective motion among the nodes. The nodes are initially uniformly located

TABLE I
SIMULATION PARAMETER VALUES.

N	100	the number of nodes
r_{obs}	$7\,m$	the radius of the area of observation
r_r	$12\,m$	the radius of the zone of repulsion
r_o	$15\,m$	the radius of the zone of orientation
r_a	$18\,m$	the radius of the zone of attraction
v_g	$2\,cm$/time unit	the speed of each guide node
v_s	$5\,cm$/time unit	the speed of each standard node

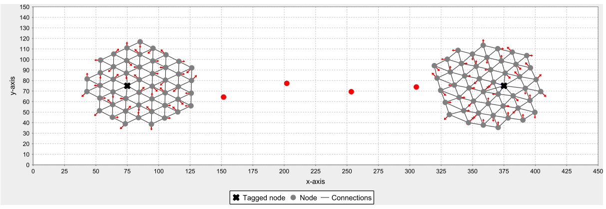

Fig. 2. The coverage achieved when 100 nodes are originally located in the central $10\,m \times 10\,m$ of a $450\,m \times 150\,m$ plane: two guide nodes move East and West from their initial positions in the centre of the plane.

in a $10\,m \times 10\,m$ area at the centre of the plane. Each guide node is initially located at the centre of the plane and moves at $2\,cm$/time unit until it reaches its destination where it stops. The standard nodes follow the guide nodes and eventually split up into clusters. Connectivity between the clusters is maintained by immobilising certain nodes at the edges of their respective clusters if the current movement step would disconnect the clusters from each other.

Note that the shapes of the emerging clusters that surround the guide nodes are not circular. The guide node is surrounded by nodes within its ZoA. Beyond this distance the nodes apply their standard pattern of alignment to their adjacent nodes. Neither the zone-based model (Rule 0) nor the particle-based model consider nodes outside the ZoA or a radius of D from the guide node. The guide node is therefore surrounded by nodes within its ZoA or radius of D. Beyond this distance the nodes apply their standard pattern of alignment to their adjacent nodes.

B. Coverage on a 2D surface with bounds

The next three experiments study node movement in the presence of boundaries and barriers. Although the nodes cannot cross the barriers, they can sense each other across the barriers. The nodes are initially uniformly located an a $10\,m \times 10\,m$ area near the bottom-left corner of a plane whose dimensions are reduced to $110\,m \times 110\,m$. Fig. 3 shows the final spatial distribution of the 100 nodes. The plane is eventually covered maintaining an hexagonal pattern as far as possible.

The motion is constrained by the presence of barriers which make it more difficult for the nodes to reach a spatially uniform distribution. Figs. 4 and 5 show that an efficient node distribution emerges nevertheless. A spatial distribution finally emerges whose central area is similar to that shown in Fig. 1.

C. Coverage on a 3D surface

The next experiment considers the coverage attained on a surface

$$z = f(x, y) = ae^{-((x-x_0)^2+(y-y_0)^2)/s}$$

which places a hill centred on (x_0, y_0) where a denotes the scale (height) and s the shape (steepness) of the hill. Note that the movement decision of node i will not consider those nodes that are hidden by the terrain (not in line-of-sight and therefore disconnected) from node i. We assume that the antenna of each

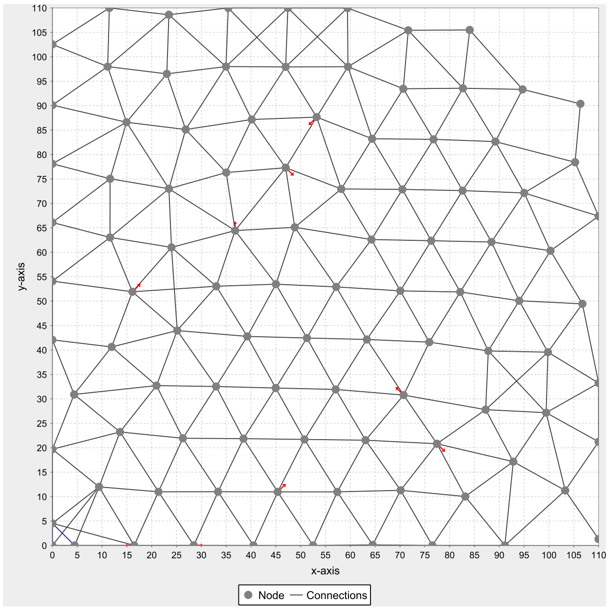

Fig. 3. The coverage achieved when 100 nodes are originally located in the bottom left $10\,m \times 10\,m$ quadrant of a $110\,m \times 110\,m$ plane.

node is located 0.1m above the ground to prevent a slightly curved surface from giving rise to disconnections.

We construct a high, slowly rising hill located on a $110\,m \times 110\,m$ plane. The hill is centred on $(x_0, y_0) = (40, 40)$ and is of height $a = 20$ and shape $s = 200$. Fig. 6 shows the final spatial distribution of the 100 nodes when the nodes are initially uniformly located in a $10\,m \times 10\,m$ area at the bottom-left of the plane. The coverage is not optimal in the vicinity of the hill. This can be explained in part by noting that the

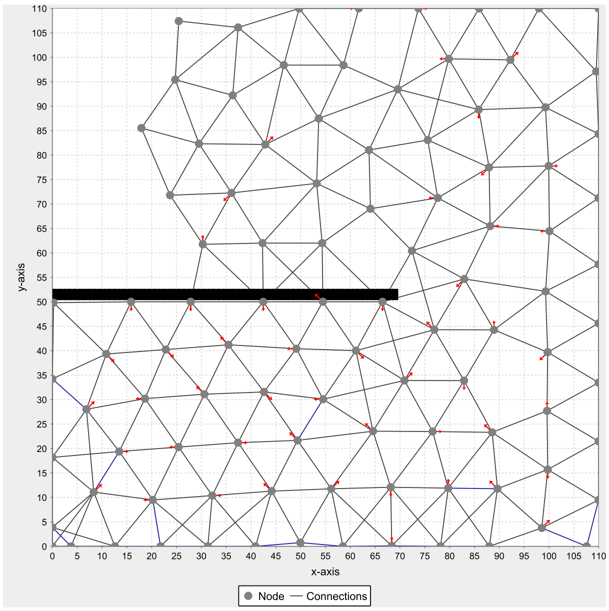

Fig. 4. The coverage achieved when 100 nodes are originally located in the bottom left $10\,m \times 10\,m$ quadrant of a $110\,m \times 110\,m$ plane with one barrier.

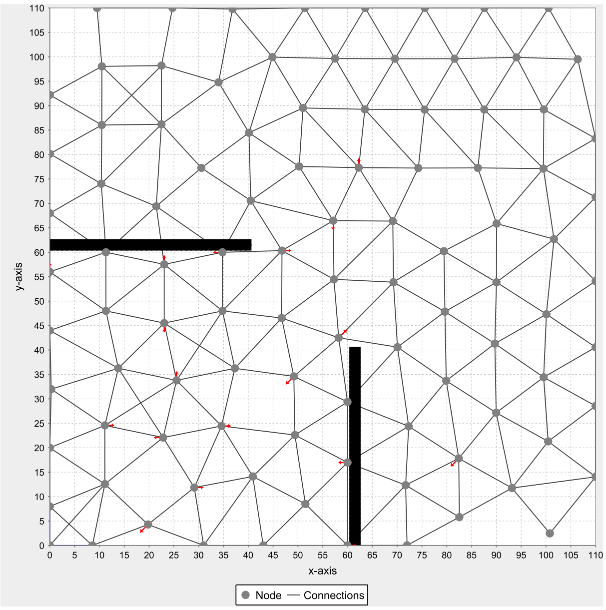

Fig. 5. The coverage achieved when 100 nodes are originally located in the bottom left $10\,m \times 10\,m$ quadrant of a $110\,m \times 110\,m$ plane with two barriers.

attractive forces between any pair of nodes further than $D\,m$ apart facilitates "flooding" around the hill. Nodes located on the slope of the hill are connected by line-of-sight only with those nodes that are, to within a small angular field, either directly in front or directly behind them. The attractive force is therefore restricted to act on pairs of nodes on the same side of the hill. The attractive forces thus encourage the nodes to move along the contour lines.

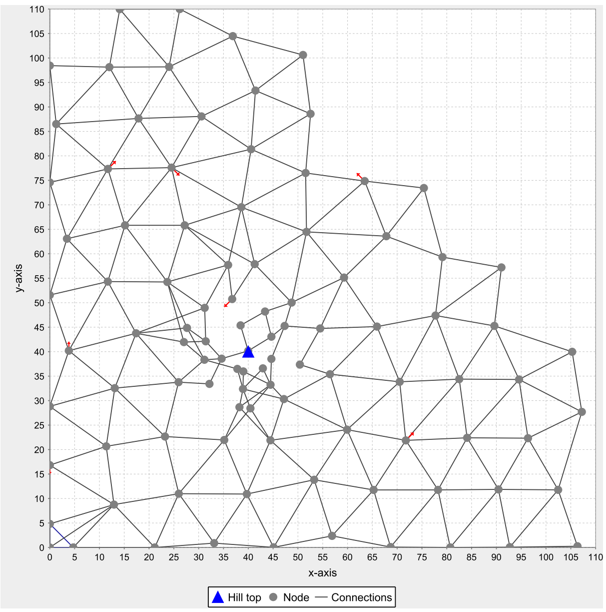

Fig. 6. The coverage achieved when 100 nodes are originally located in the bottom left $10\,m \times 10\,m$ quadrant of a $110\,m \times 110\,m$ plane with a high, gently sloping hill located at (40,40).

A guide node could be instructed to move to the top of the hill to attract nodes and offer adequate coverage. However, such guide attraction has to be relatively strong to compensate for the forces of attraction diverting the nodes around the hill and to ensure that the nodes following the guide node are sufficiently close to maintain line-of-sight contact on the slope of the hill.

IV. Network data traffic

The experiments presented thus far have investigated the spatial node distribution emerging from the node movement rules which are designed to maximize area coverage. In this section we will investigate whether the emerging spatial distribution of the nodes allows for the efficient processing of data traffic.

We rely on the work of Crowcroft *et al.* [4] who developed a model of data rate control in a MANET. In this model, the nodes earn credits for making their resources (bandwidth and battery power) available when they act as transits which receive and forward the calls that originate at other nodes.

Each originating node sends data at a rate that is proportional to the amount of credits that the node currently possesses. Each node therefore has an incentive to act as a relay for traffic that originates at other nodes, since by so doing it is able to acquire the credits that it needs in order to pay other nodes to transport its calls. In addition, credits are also redistributed from those nodes with an over-provision of credits to those nodes with an under-provision of credits. Credit redistribution thus allows nodes which attract no transit traffic to transmit data at a minimal rate. The data rates at each node converge towards utilising the resources as fully as possible so that a data transfer of a given size will complete as soon as possible.

Recall the experiment of Fig. 2: the two guide nodes move to their respective targets and are followed by the other nodes. The original cluster of nodes divides into two groups which maintain inter- and intra-cluster radio connectivity. The random number seeds in the simulation are chosen such that the clusters are of significantly different sizes. We assume that each node, at the instants of a Poisson process, encounters something worth reporting and transmits a stream of data (a message) to one of the guide nodes. The message lengths are assumed to be exponentially distributed. The guide nodes are responsible for forwarding these data to an outside agency.

The bandwidth of each guide node and each standard node is set equal to 10 units of data per time unit. Each standard node creates an average of 5.5 units of data every 30 time units. Any data transmission not completed after 100 time units is discarded. The expected data traffic generated by 96 nodes (4 of the 100 nodes are immobilised) amounts to $5.5 \times 96/30 = 17.6$ units of data per time unit, which is less than the total bandwidth of 20 units of data per time unit that is available at the two guide nodes. Thus, if the cluster sizes are approximately equal, the guide nodes are able to accommodate the offered traffic.

TABLE II
EFFICIENCY OF DATA TRANSMISSION.

	Total	Left cluster	Right cluster
Standard nodes	96	65	31
Expected traffic	17.6	11.9	5.7
Guide bandwidth	20.0	10.0	10.0
Avg. transmission completed	87.7 %	81.8 %	99.9 %
Min. transmission completed	75.0 %	75.0 %	98.8 %
Sdev. transmission completed	8.9 %	2.8 %	0.1 %

We can now specify the *efficiency* with which the data traffic are processed. First, the total data rate which is the average amount of data sent per time unit by all the nodes should be close to 17.6, thus minimising the data discarded, or equivalently, maximising the proportion of data transmissions completed.

Second, the nodes should be treated equally. Consider the proportion of messages that are successfully transmitted from each node. The average value of the message completion probability should be large and the standard deviation of the completion probabilities should be small. A low average completion probability would indicate that many of the nodes are not able to report their observations. A high standard deviation would indicate that some nodes perform worse than others so that the data gathered from the area covered by the nodes would be biased.

Table II shows that nearly 90 % of all data transmissions are completed. The cluster sizes are significantly different. The bandwidth of the guide node in the right hand cluster is on average far from fully utilised, thus almost all of the transmissions are successful. The guide node in the left hand cluster is overloaded: the average data traffic sent to the guide node exceeds the bandwidth of the guide node by almost 20 %. Nonetheless, some 80 % of all data transmissions from the left hand cluster are completed.

V. CONCLUSIONS

The goal of this study is to investigate a distributed scalable method whereby the nodes move autonomously in order to maximise the coverage of the network, while at the same time ensuring that the mobile nodes do not move so far away from each other (thus trivially maximising the coverage) that they become disconnected.

This paper presents an extension of the self-deployment problem. One or more informed nodes, which we refer to as guide nodes, are initially surrounded by a cluster of connected nodes. The guide nodes are instructed by an external agency to move to locations of interest. The application of a set of local rules causes the nodes to follow the guide nodes and establish an optimal coverage in the areas of interest. If the areas of interest are sufficiently far apart, the motion may result in the nodes forming separate clusters, each centred on a guide node. Where necessary, nodes detach themselves from the clusters and form a path connecting the clusters should the clusters move out of radio contact.

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