Modelling Collaborative Motion in Mobile Ad Hoc Networks

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***Abstract*—A mobile ad hoc network (MANET) is a wireless network formed by a set of mobile nodes in a self-organising way without relying on any established infrastructure. All nodes in a MANET are potentially mobile and can be connected dynamically in an arbitrary manner. All nodes of these networks behave as routers and take part in the discovery and maintenance of routes to other nodes in the network. Mobility models that accurately represent the movements of mobile nodes play a useful role when simulating new protocols and applications in MANETs. Synthetic mobility models can be broadly divided into two categories: individual mobility models represent the independent movements of individual nodes; collective mobility models represent the motions of groups of nodes. In this paper we develop a collective mobility model, the adaptive mobility model, and apply it to investigate how mobile nodes can autonomously arrange themselves into a formation that maximises their area coverage.**

I. INTRODUCTION

A mobile ad hoc network (MANET) is a collection of mobile nodes with no pre-established infrastructure forming a temporary network [1]. All communication in a MANET occurs through a wireless medium. Realistic mobility models are needed in simulations in order to evaluate system and protocol performance. For example, to simulate a new protocol, it is necessary to develop and use mobility models that accurately represent the movement of the mobile nodes that will eventually utilise the given protocol. It is then possible to determine whether or not the proposed protocol will be useful when implemented. It is therefore imperative that accurate mobility models are chosen [2].

Currently, two types of mobility models have been used to simulate networks: traces and synthetic models [4]. Traces are mobility patterns that are observed in real life systems. Traces provide accurate information, especially when they involve a large number of nodes and appropriately long observation periods. However, new MANET environments often have to be modelled in situations where traces have not yet been recorded. In this situation it is necessary to use synthetic models.

Since mobile nodes in MANETs can move in many different ways, it is not simple to choose an appropriate synthetic mobility model. Synthetic mobility models can be broadly divided into two categories: individual mobility models represent the independent movements of individual nodes; collective mobility models represent the movements of groups of nodes.

The random walk mobility model [3, 5] is one of the most widely used individual mobility models in MANET simulation. In this model, the movement direction and speed at time $t+\Delta t$ does not depend upon the direction and speed at time t. This characteristic makes the mobility model memoryless, and generates an unrealistic movement for each mobile node, presenting sharp turns, sudden stops, and accelerations.

Other models based on the random walk mobility model were proposed in [6, 7]. The random waypoint mobility model [9] is based on the random walk mobility model. This model includes pause times between changes in destination and speed. The boundless simulation area mobility model [8] is also an individual mobility model. The Gauss-Markov mobility model that was originally proposed for the simulation of a personal communication system (PCS) [10] is also an individual mobility model. This model was used for the simulation of a MANET [11]. In brief, the boundless simulation area and Gauss-Markov mobility models are enhancements of the random waypoint model. These two models introduce the concept of memory, where the speed/direction (boundless) and direction of a movement (Gauss-Markov) are relative to the previous state of the corresponding node.

Group mobility models are used to represent the movement of a group of mobile nodes. These models have been used to predict the partitioning of MANETs, which is defined as a wide-scale topology change caused by the group movement behaviour of the mobile nodes [12].

The reference point group mobility model was developed by Hong *et al.* [13], where for each mobile node there is an associated reference point which defines the group movement. Another group mobility model is the biological mobility model [14]. In this model each node attempts to maintain a minimum distance between itself and all the other nodes at all times. This paper presents the adaptive group behaviour mobility model [15] which uses *basis behaviours* as general building blocks for synthesising artificial group behaviour in multi-agent systems. These basis behaviours are adapted to model the mobility of mobile nodes in a MANET.

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II. THE ADAPTIVE GROUP BEHAVIOUR MOBILITY MODEL

This section presents the concept of basis behaviours that was proposed by Matrić [15] as general purpose building blocks for synthesising artificial group behaviour in multi-agent systems. The model presents a self-organising group formation in two-dimensional space, and the model is used to investigate the spatial dynamics of a flock of nodes. The model shows how differences among individuals influence the group structure, and how individuals employing simple, local rules can change their spatial position within a group (move to the centre, the front, or the periphery) in the absence of information on their current position within the group as a whole. The basis behaviours are adapted to model collective motion among the nodes of a MANET.

This model, referred to as the flocking model, is based on simple rules of avoidance, which yields motion without collisions, termed safe-wandering. Avoidance in groups can be achieved by dispersion, a behaviour that reduces local interference. In contrast to goals that minimise interaction by decreasing physical proximity, other goals may involve the exchange of resources through proximity, which is achieved through aggregation. Aggregating with other nodes or moving to a specific location involves some form of homing. Any collective movement of a group requires coordinated motion in order to minimise interference. Following and flocking are two common forms of such structured group motions.

In this section the following set of basis behaviours is presented:

- safe-wandering: minimises collisions between nodes and between nodes and obstacles.
- following: allows nodes to follow guide nodes
- aggregation: gathers the nodes in order to establish a maximum distance between them
- dispersion: spreads out the nodes over an area in order to establish a minimum distance between them
- homing: allows nodes to reach a goal region or location.

We use these basis behaviours to build a flocking behaviour model by combining the outputs of safe-wandering, dispersion, aggregation, and homing. To do this, the strategies used to implement each of the basis behaviours in the collective motion are presented in the form of algorithms. Their formal definitions can be found in [15].

A. Safe-Wandering

Inspired by animal navigation routines [14], safe-wandering is a combination of two rules: one rule prevents a node from colliding with obstacles, and another rule keeps the node turning randomly without moving. The avoidance component consists of two complementary behaviours, one for avoiding kin and another for avoiding everything else. The *Avoid-Kin* behaviour takes advantage of group homogeneity; since all nodes execute the same strategy, the algorithm can take advantage of the resulting spatial symmetry. The *Avoid-Everything-Else* behaviour prevents the nodes from remaining near to obstacles such as barriers and bounds for a long period of time. The safe-wandering algorithm is given by Algorithm 1.

Algorithm 1 The Safe-Wandering algorithm

```
Avoid-Kin:
if node $j$ is within d-avoid of node $i$ then
    if node $j$ is on the left then
        node $i$ turns right and moves forward by $V\Delta t$
    else
        node $i$ turns left and moves forward by $V\Delta t$.
    end if
end if
Avoid-Everything-Else:
if an obstacle is within d-avoid of node $i$ then
    if the obstacle is on the left then
        node $i$ turns right and moves forward by $V\Delta t$
    else if the obstacle is on the right then
        node $i$ turns left and moves forward by $V\Delta t$
    else
        node $i$ backs up and turns randomly.
    end if
end if
Random-Turn: node $i$ turns randomly without moving.
```

B. Following

Following is achieved by a simple rule that steers the nodes towards the position of the guide nodes or leaders. A guide node is instructed to move to a specified location, and the nodes follow the guide node. If the guide node is present within a distance *d-follow* of node i, then node i moves toward the guide node. If several guides are present within a distance *d-follow* of node i, then node i moves toward the nearest guide. The velocity of the guide nodes must be less than the velocity of nodes. This condition ensures that nodes can follow the guide nodes. The Following algorithm is given by Algorithm 2.

C. Dispersion

Robust dispersion behaviour can be designed as an extension of safe-wandering. Avoidance in safe-wandering reacts to the presence of a single node. In contrast, the dispersion algorithm computes the local centroid *centroid-disperse* to determine the density distribution of nearby nodes (nodes within a distance *d-disperse* of node i). Nodes use this *centroid-disperse* to decide in which direction to move. If one or more nodes are within *d-disperse* of node i, node i moves away from the local *centroid-disperse*.

Dispersion can be viewed as an ongoing process which maintains a desired distance between the nodes while they are performing other tasks such as communicating with each other. The Dispersion algorithm is given by Algorithm 3.

Algorithm 2 The Following algorithm

```
if one or more guide nodes are within d-follow of node $i$ then
    node $i$ moves towards the nearest guide node by $V\Delta t$.
end if
```

Algorithm 3 The Dispersion algorithm

```
if one or more nodes are within d-disperse of node $i$ then
    compute the local centroid centroid-disperse of the nearby nodes of node $i$; node $i$ moves away from centroid-disperse by $V\Delta t$.
end if
```

D. Aggregation

Aggregation is the inverse of dispersion, where the goal of aggregation is to achieve and maintain a maximum distance between nodes. The aggregation algorithm computes the local centroid *centroid-aggregate* to determine the density distribution of nearby nodes (nodes within a distance *d-aggregate* of node i). Nodes use this *centroid-aggregate* to decide in which direction to move. If one or more nodes are within *d-aggregate* of node i, node i moves towards the local *centroid-aggregate*. The Aggregation algorithm is given by Algorithm 4.

E. Homing

The goal of homing behaviour is to move the nodes toward a specified location called *home*. Homing behaviour can be implemented by a simple pursuit strategy, where the home location is predefined and known by the nodes. Matrić [15] found that the trajectories of homing behaviour are far from optimal, where homing is effective as long as the density of nodes is low. Matrić proved that homing becomes increasingly inefficient as the group size grows. The Homing algorithm is given by Algorithm 5.

F. Flocking Behaviour

In the spatial domain, the outputs of all the basis behaviours are in the form of direction and velocity vectors, so the sums of such vectors produce coherent higher-level behaviours. To illustrate this method we implement a flocking behaviour model by combining the outputs of safe-wandering, aggregation, dispersion and homing. Intuitively, aggregation keeps the nodes from getting too far from each other, dispersion keeps the nodes from getting too close, homing moves the flock of nodes toward some location and safe-wandering prevents nodes from collisions.

The choice of the distances *d-avoid*, *d-disperse* and *d-aggregate* depends on the characteristics of the desired spatial distribution of the nodes. In our flocking model, the constituent basis behaviours are complementary and these distances satisfy the following condition

$$\textit{d-avoid} < \textit{d-disperse} < \textit{d-aggregate}.$$

Algorithm 4 The Aggregation algorithm

```
if one or more nodes are within d-aggregate of node $i$ then
    compute the local centroid centroid-aggregate of the nearby nodes of node $i$; node $i$ moves toward the local centroid-aggregate by $V\Delta t$.
end if
```

Algorithm 5 The Homing algorithm

```
if node $i$ is at home then
    node $i$ stops moving
else
    node $i$ moves towards the location of home by $V\Delta t$.
end if
```

The local centroid C_i, for both dispersion and aggregation, is computed as follows

$$C_i = \sum_{j=1}^{N} p_j / N$$

where N is the number of nodes that are present within the aggregation/dispersion distance of node i and $p_j = (x_j, y_j)$ is the position of node j.

Some adjustments were made to the original flocking behaviour algorithm to present a more realistic model of motion in MANETs. First, each node i is surrounded by a circular zone of orientation where the ZoO stabilises the node movements. The radius *d-orientate* of the ZoO must satisfy the following condition

$$\textit{d-disperse} < \textit{d-orientate} < \textit{d-aggregate}.$$

Next, the safe-wandering behaviour was changed so that if node j is within *d-avoid* of node i, node i moves away from node j. The Flocking algorithm is given by Algorithm 6.

Note that flocking is a collective motion that requires that all the nodes stay within a flocking range. Unlike aggregation, flocking not only requires the nodes to stay together, but also to move toward a goal location *home*. Flocking is more efficient than individual homing as the number of nodes increases. Matrić [15] showed that the performance of flocking is dependent on the size of the flock where small flocks are less stable than larger flocks.

III. MAXIMISING AREA COVERAGE ON A 2D SURFACE

In this section, a collective mobility model is introduced and studied in order to maximise the area coverage on a 2D surface. Collective mobility models are generally used in mobile MANETs to predict the partitioning of MANETs. This mobility is defined as a wide-scale topology change, caused mainly by the group movement behaviour of the mobile nodes [2]. Collective mobility movements are usually used to coordinate the movement of clusters of nodes in order to achieve particular goals.

Our collective mobility model is based on the concept of basis behaviour proposed by Matrić [15] and is designed to spatially distribute the mobile nodes in a MANET to in order to maximise their area coverage, which is defined as the total area observed by the nodes [16].

The collective model is represented by the application of three basis behaviours derived from Matrić [15]. These basis behaviours are Safe-Wandering, Dispersion and Aggregation. The ZoO, derived from the biological mobility model, is also included in this model where it is used to stabilise the nodes.

Algorithm 6 The Flocking algorithm

```
if guide nodes are present in any zone then
    node $i$ moves towards the nearest guide node.
end if
if node $j$ is within d-avoid of node $i$ then
    node $i$ moves away from node $j$ by $V\Delta t$.
end if
if no nodes are within d-avoid of node $i$ then
    if one or more nodes are within d-disperse of node $i$ then
        compute the local centroid centroid-disperse of the nearby nodes of node $i$; node $i$ moves away from centroid-disperse
    else
        if one or more nodes are within d-orientate of node $i$ then
            node $i$ does not move
        else
            if one or more nodes are within d-aggregate of node $i$ then
                compute the local centroid centroid-aggregate of the nearby nodes of node $i$; node $i$ moves towards centroid-aggregate
            else
                node $i$ does not move.
            end if
        end if
    end if
end if
```

The first experiment investigates the spatial distribution of the nodes where nodes are free to move away from each other in *safe-wandering*, *aggregation* and *dispersion* zones. In a *safe-wandering* zone a node reacts to the presence of a single node and moves away from it. However, in a *dispersion* zone node i uses the local distribution of all of the nearby nodes (nodes within a distance *d-disperse* of node i) in order to decide in which direction to move. The simulation is run for up to $20.000s$ of simulated time. The node movements are updated every $0.1s$. The simulation parameter values are given in Table I.

Localisation error is modelled by adding an error to the distance between nodes. The distance $r_n(t) - r_i(t) = (x,\ y)$ between nodes n and i at time t is computed as follows

$$x = x + E(0.05x)\cos(\theta)$$
$$y = y + E(0.05y)\sin(\theta)$$

where $E(z)$ is a random variable sampled from an exponential distribution with parameter z, and θ is a random variable sampled from a uniform distribution in the range $[-\pi, \pi]$.

TABLE I
SIMULATION PARAMETER VALUES.

ρ_r	$9\,m$	The radius of the zone of safe-wandering.
ρ_r	$12\,m$	The radius of the zone of dispersion.
ρ_o	$15\,m$	The radius of the zone of orientation.
ρ_a	$17\,m$	The radius of the zone of aggregation.
ρ_d	$56\,m$	The radius of node-to-node radio transmission.
ρ_{obs}	$7\,m$	The radius of the area of observation.
D	$13\,m$	The desired distance between adjacent nodes.
V_g	$2\,cm$/time unit	The speed of each guide node.
V_s	$5\,cm$/time unit	The speed of each standard node.

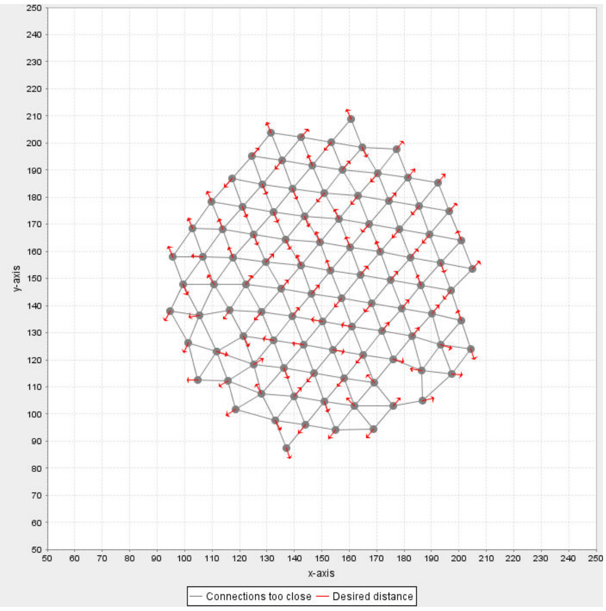

Fig. 1. The coverage achieved when 100 nodes are originally located in the central $10m \times 10m$ of a $300m \times 300m$ plane.

Figure 1 shows the final spatial distribution of 100 nodes. The nodes are initially located in a $10m \times 10m$ area at the centre of a $300m \times 300m$ plane. The boundaries of the plane are sufficiently far away to ensure that nodes will not reach the edge of the network during the simulation. Most of the nodes locate themselves approximately $12.5m$ apart at the vertices of a hexagonal lattice forming an approximately optimal area coverage.

IV. MAINTAINING CLUSTER CONNECTIVITY

In some MANET applications such as battlefield communication and disaster relief, nodes collaborate amongst themselves and follow guide nodes or leaders. The adaptive group mobility model was modified to represent the motion induced by the presence of guides. A guide node moves to a specified location and induces a collective motion 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.

In the case of more than one guide node, the nodes may split up into different clusters and each cluster may follow a different guide node. The clusters may lose radio connectivity among themselves when they move too far away from each other. In order to maintain radio connectivity between the clusters, some nodes leave their clusters and act as transit nodes to connect the clusters.

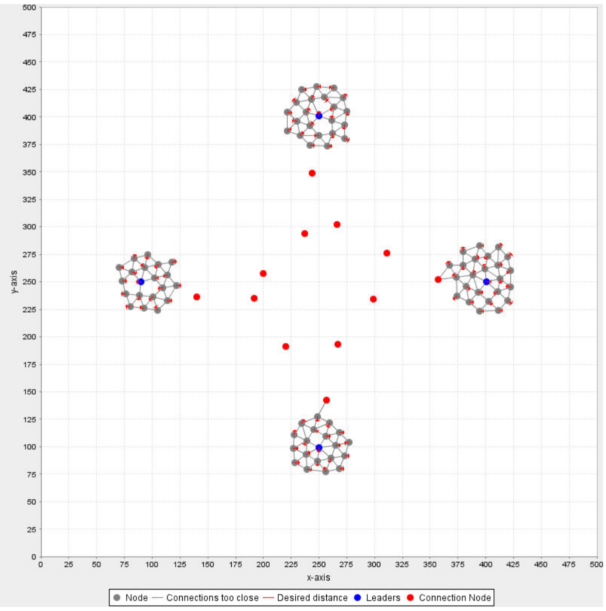

Fig. 2. The coverage achieved when 100 nodes are originally located in the central $10m \times 10m$ of a $500m \times 500m$ plane: four guide nodes are initially located in the centre of the plane; the four guide nodes move North, South, East and West respectively.

In order to prevent disconnection between clusters, the distance between these transit nodes must be less than r_d, the radius of node-to-node radio transmission. In addition, transit nodes should not be too close to each other in which case too many nodes will act as relays between the clusters and spend their resources far away from the vicinity of the guide nodes where observations have to be made. Each node K calculates its new movement step. The movement step is only performed if there are one or more nodes N within a radius r_d of node K. In this case the movement can be executed without losing radio connectivity and node K executes the movement step. If node K would lose radio connectivity if the movement step were executed, then node K must verify whether another node R can be used as a relay between node K and any of the nodes N. Such a node R must be no more than r_d distance from nodes K and N. If such a relay node R cannot be found, then node K is immobilised, the movement step of node K is denied, and connectivity with node N is preserved.

Figure 2 shows the final spatial distribution of the nodes when the nodes are initially uniformly located in a $10m \times 10m$ area at the centre of a $500m \times 500m$ plane. There are four guide nodes. The guide nodes are initially located at the centre of the plane. The guide nodes move at $2cm/s$. The first guide node moves until it reaches $(90, 250)$ where it stops. The second guide node moves until it reaches $(410, 250)$ where it stops. The remaining two guide nodes move until they reach $(250,\ 410)$ and $(250,\ 90)$ respectively where they stop.

The nodes follow the guide nodes and split up into four clusters. Connectivity between the four clusters is maintained by immobilising nodes at the edges of their respective clusters. This is done when the current movement step would disconnect the clusters from each other. The immobilised nodes form a ring in the centre of the network to maintain connectivity between the four clusters. When the guide nodes reach their goals they stop moving. In this case the nodes apply the standard rules of safe-wandering, dispersion, orientation and aggregation to achieve their maximum area coverage. This can be observed in Fig. 2 where nodes surround the guide nodes in approximately hexagonal lattices.

V. CONCLUSION

This paper presents a collective mobility model, the adaptive group mobility model, where the nodes move autonomously in order to maximise the area coverage of the network. At the same time, these nodes ensure that they do not move so far away from each other that they disconnect themselves. The adaptive mobility model is used to maximise the area coverage. The model shows that nodes are able to locate themselves approximately at the vertices of an hexagonal lattice.

The adaptive group mobility model was also investigated in the presence of guide nodes. A guide node moves to a specific vicinity where the observation must happen. The rest of the nodes follow the guide node. In the case of more than one guide node, the nodes may split up into different clusters each following a different guide node causing the clusters to disconnect from each other. In this event, some nodes leave their clusters and act as transit nodes to connect these clusters. The simulation shows that at the end of the simulation each cluster of nodes surrounds its guide node and the transit nodes formed a ring in the middle of the network.

REFERENCES

[1] L. Buttyán and J.P. Hubaux. Stimulating Cooperation in Self-Organizing Mobile Ad Hoc Networks, Mobile Networks and Applications, 8 (5), pp. 579-592, 2003.

[2] V. A. Davies. Evaluating mobility models within an ad hoc network, Master of science thesis, Mathematical and Computer Sciences Department, Colorado School of Mines, Golden, Colorado, 2000.

[3] T. Camp, J. Boleng and V. Davies. A survey of mobility models for ad hoc network research, Wireless Communication and Mobile Computing (WCMC), vol. 2, no. 5, pp.483-502, 2002.

[4] M. Sanchez and P. Manzoni. A Java-based ad hoc network simulator, In Proceedings of the SCS Western Multiconference Web-based Simulation Track, Jan. 1999.

[5] M.M. Zonoozi and P. Dassanayake. User mobility modelling and characterization of mobility patterns, IEEE Journal on Selected Areas in Communications, vol. 15, no. 7, pp. 1239-1252, 1997

[6] S. Basagni, I. Chlamtac, V. R. Syrotiuk and B. A. Woodward. A distance routing effect algorithm for mobility (DREAM), in Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM '98), pp. 76-84, Dallas, Tx, USA, October 1998.

[7] Y.B. Ko and N.H. Vaidya. Location-aided routing (LAR) in mobile ad hoc networks, in Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM 98), pp. 66-75, Dallas, Tx, USA, October 1998.

[8] Z. Haas. A new routing protocol for reconfigurable wireless networks. In Proceedings of the IEEE International Conference on Universal Personal Communications (ICUPC), pp 562-565, Oct. 1997.

[9] D. Johnson and D. Maltz. Dynamic source routing in ad hoc wireless networks. In T. Imelinsky and H. Korth, editors, Mobile Computing, pp 153-181. Kluwer Academic Publishers, 1996.

[10] B. Liang and Z.J. Haas. Predictive distance-based mobility management for PCS networks, In Proceedings of the Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'99), vol. 3, pp. 1377-1384, March 1999.

[11] V. Tolety. Load reduction in ad hoc networks using mobile servers. Master's thesis, Colorado School of Mines, 1999.

[12] C.A.V. Campos, D.C. Otero and L.F.M. de Moraes. Realistic individual mobility Markovian models for mobile ad hoc networks, Wireless Communications and Networking Conference (WCNC'04), vol. 4, pp. 1980-1985, Atlanta, Ga, USA, March 2004.

[13] X. Hong, M. Gerla, G. Pei and C.C. Chiang. A group mobility model for ad hoc wireless networks, In Proceedings of the ACM International Workshop on Modeling Analysis and Simulation of Wireless and Mobile Systems, MSWiM'99, Seattle, WA, USA, pp. 53-60, August 1999.

[14] I.D. Couzin, J. Krause, R. James, G.D. Ruxton and N.R. Franks. Collective memory and spatial sorting in animal groups, Journal of Theoretical Biology: 218, pp. 1-11, 2002.

[15] M.J. Mataric. Designing and Understanding Adaptive Group Behavior, Volen Center for Complex Systems, Computer Science Department, Brandeis University, Waltham, MA 02254. September 4, 1995.

[16] J.Göbel and A.E. Krzesinski, A model of autonomous motion in ad hoc networks to maximise area coverage, Telecommunication Networks and Applications Conference, ATNAC 2008.

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