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A New Protocol for the development and maintenance of autonomous mobile sensor networks

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Abstract— **Mobile Sensor Networks have played an important role in control and decision-making. Autonomous Mobile Sensor Networks are a step ahead. One of the required characteristics of an autonomous network is the capability to form and sustain itself while it's components (nodes) move about or go out of action. This paper proposes a protocol that can be used by network nodes to periodically evaluate and connect/reconnect with other nodes. The aim is to be able to form a connected network wherein any node can communicate with any other node in the network via a series of intermediate nodes (wherever necessary). One constraint imposed is that the node can only connect with nodes which are within a certain fixed distance from it. Another constraint is that a node can connect at most to a specific number of other nodes. Simulations are performed and the average number of nodes which form less than the maximum number of connections allowed is calculated. An attempt is made to propose a probability function describing the probability that one node connects to another. The simulations indicate that the best possibility of forming a connected network occurs when the distance over which the nodes can connect is approximately equal to the radius of the spread of the network. Also, a maximum of three connections per node result in a well-connected network.**

I. INTRODUCTION

New technologies are radically reducing the size, cost, weight and power consumption of sensors and making it more and more feasible for mobile sensor networks to be deployed in a cost-effective manner. Spatially distributed sensor networks can be very effectively used for terrain mapping, monitoring and providing data for diagnostic purposes. When such sensors are mounted on mobile robots, their effectiveness can be increased many times. Such networks provide better coverage, faster response to dynamically changing environments, better survivability and robustness to failure. If we decentralize the network, we can get the added benefits of scalability, modularity and robustness [1].

As a next step, one tries to make the network autonomous. The term autonomy is applied here in a very broad sense. The autonomous network, will build itself after its individual members have been deployed. It will move and grow so as to fulfill the task allotted to it. It will have a dynamic topology so as to adapt to changing environment. It will have decision making capabilities which will be based on the information it's own sensors will collect. In short, such a network will operate completely independent of human intervention once it has been deployed. The uses and advantages of such an autonomous mobile sensor network can hardly be overstated. They can be used for tasks such as perimeter monitoring and search and rescue operations. Such networks can form the basis for a larger network of robots with much larger computing and actuation capabilities and a much wider scope of application.

While performing all of the above, the network should also function in an energy efficient manner so as to maximize the time for which it is operational. An important issue is one of establishing connections between individual nodes of the network. One would wish for each node to have the least number of connections possible, since the maintenance of a connection requires expenditure of power. Also

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because of hardware restraints, a node may only be able to connect to nodes within a certain distance from itself. At the same time, we require the network to be connected. By connected, we mean that any node in the network should be able to communicate with any other node via a series of intermediate nodes. Also in a mobile network, the nodes are expected to move about and thus a node needs to evaluate it's connections periodically and reconnect.

The broad problem of assuring the connectivity of a network is called Topology Control. In ad hoc networks, this problem is tackled by one of two approaches: Power Control and Clustering [2]. Power control mechanisms adjust the power on a per-node basis, so that one-hop neighbor connectivity is balanced and overall network connectivity is ensured [3], [4], [5]. Ramanathan and Rosales-Hain [6] proposed to adjust incrementally node transmit powers in response to topological changes so as to maintain a connected topology using minimum power. However, topology derived from power control schemes often results in unidirectional links that create harmful interference due to the different transmission ranges among one-hop neighbors [7]. Clustering [8] consists of selecting a set of cluster-heads in a way that every node is associated with a cluster-head, and cluster-heads are connected with one another directly or by means of gateways, so that the union of gateways and cluster-heads constitute a connected backbone. Ideally, one would wish this backbone set of nodes and links to be as small as possible. The problem of clustering then can be best described by the Minimum Dominating Set and the Minimum Connected Dominating Set problems of Graph Theory. The first of these problems is known to be NP-hard even when complete topology information is available [9]. In ad-hoc distributed networks, this information is generally not available. So heuristic measures like node degree are used for choosing cluster-heads [10]. Both of these approaches assume omni-directionality of communication hardware. Recently, some work has been done on the use of directional antennas in ad hoc networks, especially to reduce noise and increase clarity of communications between nodes. A good background and information on this topic can be found in [11].

In this paper, we propose a protocol for mobile network nodes to connect to other nodes, periodically evaluate their connections and reconnect as necessary. This protocol is particularly useful for networks using directional communication hardware. The restraints imposed are that the nodes be able to connect to nodes only a certain distance away and that there is a maximum number of connections that each node is allowed to make. Simulations are done on a set of one hundred nodes, spread out. Potential Field theory is used to achieve the spreading out of the network. The average number of nodes having number of connections less than the maximum allowed is calculated. Connectivity of the resulting network is evaluated. A comparison is made with the scenario where nodes connect to each other randomly. Also, an attempt is made to identify the probability that a node will connect to another node at a distance 'd' apart. As each node takes care of it's own connections, this protocol is naturally scalable and a step towards the decentralization of the network.

II. POTENTIAL FIELD THEORY

Potential field theory is a widely used tool in mobile robotics. It is used to achieve local navigation, obstacle avoidance, deployment [12] and Formation Control [13]. It was first described by Khatib [14] and has been used extensively since.

This methods mimics the concept of Electric Potential Fields. If we assume that each node carries a like electric charge, we can define a scalar potential field and write the repulsive force of interaction between two nodes as

$$\vec{F} = -\nabla U_i. \tag{1}$$

U_i is the potential produced by the i^{th} charge or node at the node in question. It can be described as

$$U_i = \frac{k}{r_i} \tag{2}$$

where r_i is the Euclidian distance between the two nodes. In a network of nodes, using the equations (1) and (2), the net force acting on a node can be calculated to be

$$\vec{F} = -k\sum_i \frac{\vec{r_i}}{r_i^3}. \tag{3}$$

Here, $\vec{r_i} = \vec{x_i} - \vec{x}$, is the vector joining the two nodes and k is an indicator of how strong the repulsive force is. In, a real electric field, k would represent the amount of charge on each node.

Thus this method simulates an electric field and generates forces on the nodes which tend to spread them out uniformly over an area. Any obstacles present in the area can also be taken into account by assigning potentials to them. Then this method achieves deployment as well as obstacle avoidance.

III. PROPOSED PROTOCOL

As stated in the introduction, we wish to have a connected network while having each node connect to as few a number of nodes as possible. Ideally, we can achieve perfect connectivity with just two connections per node. This is illustrated in Figure 1. However, in our problem, all nodes will not be within communicating distance of each other. They may not be aware of each others presence. Hence achieving a network as in Figure 1 is impossible. Also, for achieving autonomy, the network needs to have some mechanism to handle node failures. So a new protocol is proposed.

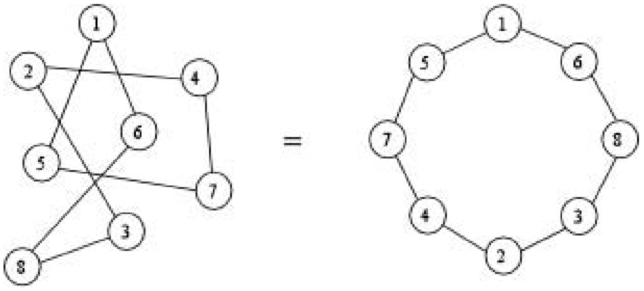

Fig. 1. A minimum of two connections per node required to form a connected network.

In this protocol, every node tries to connect to a node as far away from itself as possible. ie. Of all the nodes within it's communication radius, a node will always request a connection with the farthest node. That node, in turn, will accede to the request if the number of nodes it is connected to is less than the allowed maximum or if the requesting node is farther away from it than a node it is currently connected to. In the second case, it will break an existing connection and form a new one. If neither of these two conditions are satisfied then it will refuse the request. The requesting node will then repeat the process with the next farthest node. It will do this until all the nodes in its vicinity are exhausted or until the maximum number of connections allowed is reached. In the simulations, a hundred nodes are used in a two dimensional setting. They are concentrated in a small area from where they spread over the area they are supposed to cover. Potential field theory described above is used to achieve this. The dynamics of motion of each node is assigned to be

$$\begin{aligned} \ddot{x}_i + c\dot{x}_i &= F_{ix} \\ \ddot{y}_i + c\dot{y}_i &= F_{iy}. \end{aligned} \tag{4}$$

F_{ix} and F_{iy} are the x and y components of the force calculated in equation (3). Also to simulate variability and uncertainty, a physical characteristic of each node is varied in a certain range. In particular, the damping in each node is varied uniformly between $\pm 10\%$ of it's nominal value. As they spread, the nodes form the network. After 250 seconds, when the velocity of the nodes is almost zero, the network formed is evaluated by counting the number of nodes which have less than the maximum allowed connections. The procedure is repeated six times. The average number of such nodes is noted and this is used to evaluate the network. As a comparison, simulations were done where nodes tried to connect to other nodes randomly. i.e. A node randomly requests a connection with a node in it's communication area and that node accepts the request if it is connected to less than the max allowed number of nodes. If not, it randomly decides whether to accept the request and which current connection is to be replaced. Using the procedure explained next, the networks formed at the end of each simulation of the new protocol are tested for connectivity and the results are displayed. Also finally, an attempt is made to come up with a probability distribution function for this network. i.e. a function which specifies the probability of one node connecting to another as a function of the distance between them.

A. Connectivity of the Network

Consider a network with v nodes $\{x_1, x_2, \dots, x_v\}$ and ε edges. Define the adjacency matrix $A(v \text{ x } v)$ of this graph as

$$a_{ij} = \text{number of edges connecting } x_i \text{ to } x_j.$$

Obviously, a undirected network will have a symmetric adjacency matrix while this need not be true for a directed network. The following theorem is a slightly modified form of the one stated in [15].

Theorem 1: Let A be the adjacency matrix of a graph G with the vertex set $\{x_1, x_2, \dots, x_v\}$. *Then the* *entry in the $(i,j)^{th}$ position of A^k is the number of different (x_i,x_j)-walks of length k in G.*

Proof: The proof is by induction on k. We also use the well-known fact that if we have n paths between points 1 and 2 and m paths between points 2 and 3 then we have mn paths between points 1 and 3. For $k=1$ the result is trivial because of the definition of the adjacency matrix. Let the result be true for some $(k-1)$. Let $A^{k-1}=\left(a_{ij}^{(k-1)}\right)$. Then $a_{ij}^{(k-1)}$ is the number of different (x_i,x_j)-walks of length $k-1$ in G. Let $A^k=\left(a_{ij}^{(k)}\right)$. Since $A^k=A^{k-1}.A$, we get,

$$a_{ij}^{(k)}=\sum_{l=1}^{v} a_{il}^{(k-1)}.a_{lj}. \qquad (5)$$

Each term in the above sum is the product of the number of walks of length $k-1$ between x_i and x_l and the number of walks of length 1 between x_l and x_j. Hence the sum is the number of walks of length k between x_i and x_j. Thus by induction we have the required result.

Using the above theorem, the following Proposition can be stated.

Proposition 1: A network having an adjacency matrix A is connected if and only if there exists a natural number $p\in[1,v-1]$ *such that*

$$I+\sum_{i=1}^{p} A^i \quad > \quad 0. \qquad (6)$$

Here $A>0$ means all entries of A are greater than zero.

Proof: The proof follows naturally from Theorem 1. It is clear that the (i,j) term of $\sum_{i=1}^{p} A^i$ represents the number of walks of length at most p between x_i and x_j. If the equation given above is satisfied, then it means that every node of the network is connected to every other node by a walk of length at most p. Conversely, if the network is connected, all nodes are connected to all other nodes by walks of finite length and the condition given in the theorem will be satisfied, as an extreme case, by the natural number p which is the length of the longest walk. The identity matrix is added to A to signify that every node is connected to itself. Also p is limited by $(v-1)$ because in a network of v nodes, if a path of length more than $v-1$ exists between two nodes, then it contains a loop which can be eliminated while preserving the path. Hence the Proposition is proved.

Note that if the above proposition is true for some p then it is true for every natural number greater than p. Thus as stated in [16], it can be used as a simple test for the connectivity of a graph by calculating $I+\sum_{i=1}^{v-1} A^i$ and testing if it is element-wise greater than zero.

IV. RESULTS AND DISCUSSION

Simulations were done with the communication distance varying between 10 and 140 units and the maximum allowed connections being 2, 3 and 4. The diameter of the spread of the network varies between 130 to 170 units depending on the communication distance. The data is summarized in Figure 2.

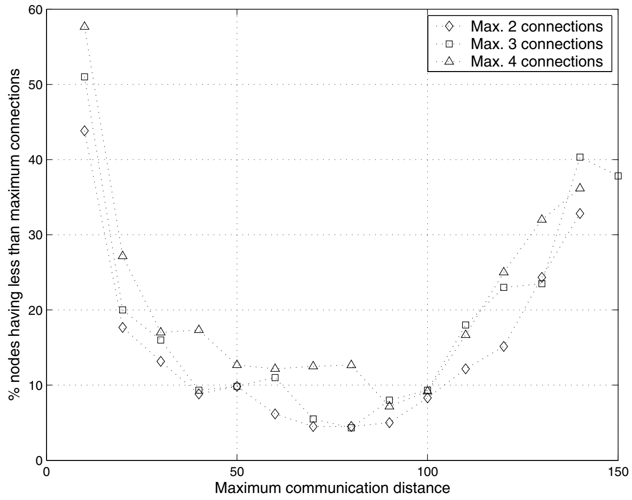

Fig. 2. Average number of nodes having less than maximum allowed connections.

As can be seen from the figure, a network where the maximum distance over which nodes can connect is 80 units and where a maximum of 3 connections are allowed per node results in only about 4% of the nodes having less than 3 connections. We can thus say that there is a very good chance of such a network being connected. To confirm this the connectivity of the networks so formed was tested. The results are displayed in Figure 3.

As can be seen, the graphs which allow a node to have at most two connections are almost never connected. The graphs that allow four connections per node perform better especially at lower communication distances. But this is to be expected as more

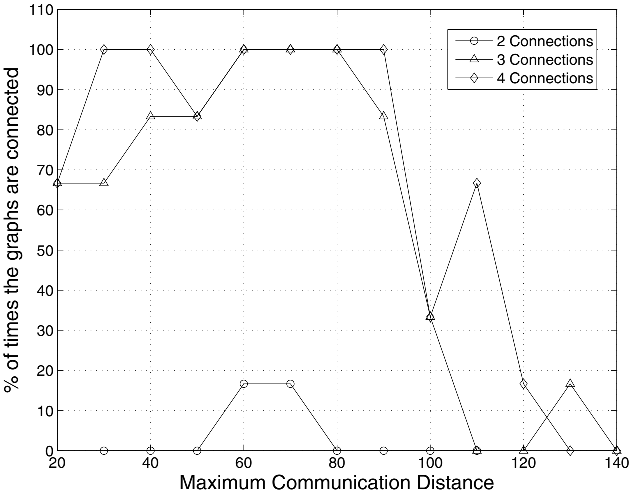

Fig. 3. Connectivity of Simulated Graphs.

connections between nodes will obviously improve connectivity.

As an indicator of the efficiency of this method we compare it to a network where the nodes connect to each other randomly. The results are shown in Figures 4 and 5.

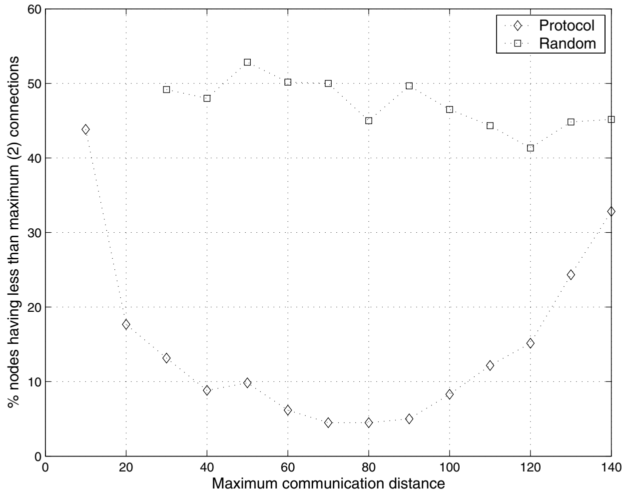

Fig. 4. Comparison of protocol with randomly connected network when a node is allowed only two connections.

As can be seen from Figures 4 and 5, the protocol works much better compared to random connections. This is because every node tries to actively connect to nodes far away from it.

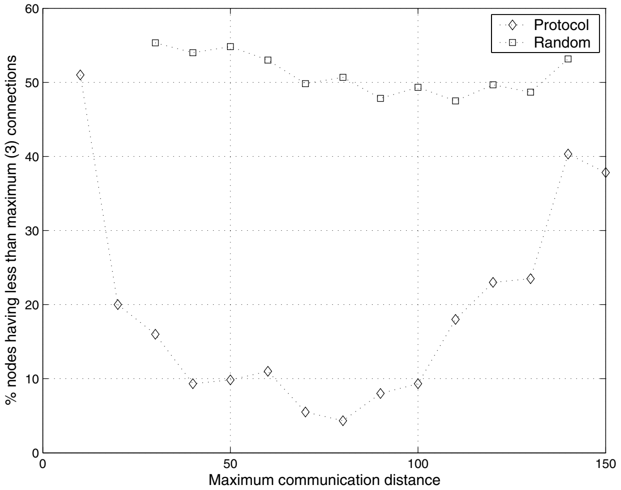

Fig. 5. Comparison of protocol with randomly connected network when a node is allowed only three connections.

It can be said from the simulations that the protocol works best when the distance over which the nodes can communicate is approximately equal to the radius of the area over which they are spread. This can act as a guideline for the choice of communications hardware for the network nodes. Also, unless reducing the distance over which the nodes communicate is a prime concern, it seems quite adequate to have a network where a node only connects to three other nodes.

An attempt is now made to propose a probability function which would describe the behavior of the network. This function will specify the probability of one node connecting to another as a function of the distance between the nodes. Because of the nature of the protocol, nodes have the highest probability of connecting to nodes which are the farthest away. The chance that a node will connect to a node near to it is little. A proposed probability function is shown in Figure 6.

One might expect the values of a and b to be zero and one respectively. However, this will not be so. To see this, note that in a uniformly spread network, a node will not have just two or three nodes near it's communication limit. It will, depending on the total number of nodes in the network, possibly have many more nodes. For example above, when the maximum distance over which nodes could communicate was 80, there were about 20 to 30 nodes at a distance of

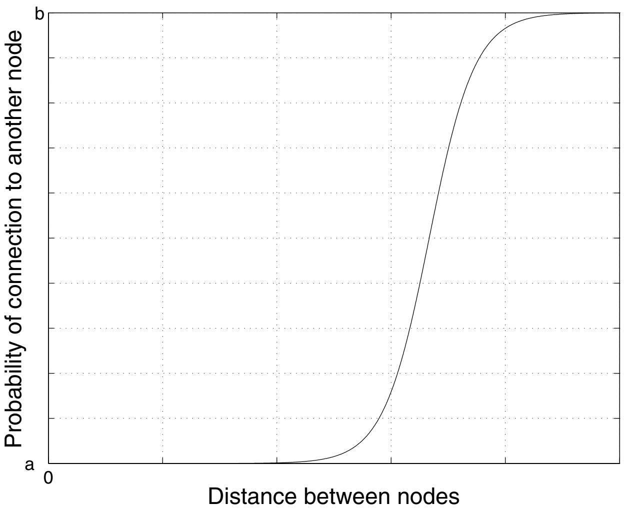

Fig. 6. Proposed probability function.

70 to 80 units from it. Out of these it will attempt to connect to two or three or whatever it's maximum number of allowed connections is. Thus the value of b will not be one but will be much less than one. Also in the protocol, every node actively tries to have the maximum number of connections it is allowed. Thus the probability that it will connect to a node near it is not zero. The exact values of *a* and *b* depend on the number of nodes in the network, the radius of spread of the network and on the maximum distance over which the nodes can communicate.

V. CONCLUSIONS

The proposed protocol can be used as an effective tool to create and maintain an effective sensor network while not spending energy on maintaining too many connections. Problems like nodes moving around or going out of action are taken care of because of the periodic evaluation, by each node, of it's own connections. The protocol is decentralized in nature as each node takes care of it's own connections. The simulations also suggest that each node needs to be able to connect only to nodes which are up to a certain distance away from it. This distance is about half the spread diameter of the network. Also each node connecting to only three other nodes is sufficient to have an adequately connected network as is seen from the very low percentage of nodes having less than the maximum number of connections. This protocol may work effectively for perimeter monitoring or search-and-locate networks.

REFERENCES

[1] A. Makarenko, T. Kaupp, H. Durrant-White, "Scalable Human-Robot Interactions in Active Sensor Networks", IEEE Pervasive Computing, Vol. 2, No. 4, pp. 63-71, 2003.

[2] L. Bao, J. J. Garcia-Luna-Aceves, "Topology management in ad hoc networks", Proceedings of MobiHoc, Annapolis, 2003, pp. 129-140.

[3] L. Hu, "Topology control for multihop packet radio networks", IEEE Transactions on Communications, Vol. 41, No. 10, pp. 1474-1481, October 1993.

[4] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, P. R. Kumar, "Power Control in Ad-Hoc Networks: Theory, Architecture, Algorithm and Implementation of the COMPOW Protocol", Proceedings of the European Wireless Conference, pp. 156-162, Florence, Italy, February 2002.

[5] H. Takagi, L. Kleinrock, "Optimal transmission ranges for randomly distributed packet radio terminals", IEEE Transactions on Communications, Vol. 32, No. 3, pp. 246-257, March 1984.

[6] R. Ramanathan, R. Rosales-Hain, "Topology Control of Multihop Wireless Networks using Transmit Power Adjustment", Proceedings of IEEE Conference on Computer Communications (INFOCOM), March 2000.

[7] R. Prakash, "Unidirectional links prove costly in Wireless Ad-Hoc Networks", Proceedings of the Discrete Algorithms and Methods for Mobile Computing and Communications - DialM, Seattle, WA, August 1999.

[8] P. Krishna, N. Vaidya, M. Chatterjee, D. Pradhan, "A cluster-based approach for routing in dynamic networks", ACM SIGCOMM Computer Communication Review, pp. 49-65, April 1997.

[9] A. Amis, R. Prakash, T. Vuong, D. T. Huynh, "MaxMin D-Cluster Formation in Wireless Ad Hoc Networks", Proceedings of IEEE Conference on Computer Communications (INFOCOM), March 1999.

[10] L. Jia, R. Rajaraman, T. Suel, "An Efficient Distributed Algorithm for Constructing Small Dominating Sets", Twentieth ACM Symposium on Principles of Distributed Computing PODC'01, Newport, Rhode Island, August 2001.

[11] R. R. Choudhury, X. Yang, R. Ramanathan, N. H. Vaidya, "Using Directional Antennas for Medium Access Control in Ad Hoc Networks", MOBICOM'02, Atlanta, GA, September 2002, pp. 59-70.

[12] A. Howard, M. J. Matarić, G. S. Sukhatme, "Mobile Sensor Network Deployment using Potential Fields: A Distributed, Scalable Solution to the Area Coverage Problem", Proceedings of the 6^{th} International Symposium on Distributed Autonomous Robotics Systems (DARS02) Fukuoka, Japan, June 2002.

[13] F. E. Scheider, D. Wildermuth, H.-L. Wolf, "Motion coordination in formations of multiple mobile robots using a potential field approach", Distributed Autonomous Robotics Systems, Vol. 4, pp. 305314, Springer, 2000.

[14] O. Khatib, "Real-time obstacle avoidance for manipulators and mobile robots", International Journal of Robotics Research, Vol. 5, No. 1, pp. 9098, 1986.

[15] J. Xu, "Theory and Application of Graphs", *Kluwer Academic Publishers*, MA, pp. 64, 2003.

[16] R. A. Horn, C. R. Johnson, "Matrix Analysis", *Cambridge University Press*, Cambridge, UK, pp. , 1999.