Maximum System Lifetime Routing in Ad-Hoc Networks
A Critical Study

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Abstract— **Since some or all of the nodes in a mobile ad-hoc network (MANET) rely on batteries for their energy, one of the key design criteria for a wireless network is that of power conservation. This paper attempts a critical appreciation of the Maximum System Lifetime (MSL) routing algorithm suggested by Jae-Hwan Chang and Leandros Tassiulas in "Energy Conserving Routing in Wireless Ad-Hoc Networks". They formulate routing in a power-controlled wireless network as an optimization problem with the goal of maximizing the time until the batteries of the nodes drain out. To this end, they propose that traffic be routed such that the energy consumption is balanced among the nodes in proportion to their energy reserves, instead of routing to minimize the absolute consumed power.**

I. INTRODUCTION

An ad-hoc network is a multi-hop wireless network where all nodes cooperatively maintain network connectivity without a centralized infrastructure. If these nodes change their positions dynamically, it is called a mobile ad-hoc network (MANET). Due to the limited transmission range of wireless nodes, as well as the rapid change in network topology, multiple network hops may be needed for one node to exchange data with another across the network. Thus, each node operates not only as a host but also as a router, forwarding packets for other nodes in the network that may not be within the transmission range of their destination. The nodes participate in an ad-hoc routing protocol that allows them to discover multi-hop paths through the network to any other node. Different routing protocols use different metrics to dynamically determine the optimal path between the sender and the recipient. These cost parameters include number of hops, delay, link quality, location stability and power conservation.

The problem of routing in MANETs is compounded by node mobility [15], which results in two conflicting goals—frequent topology updates are required to optimize routes, yet frequent updates result in higher message overhead, bandwidth wastage and power loss. The most common cost metric used for determining the optimum routing path is shortest delay or fewest number of hops, as in the case of Dynamic Source Routing (DSR) [7], Destination-Sequenced Distance Vector (DSDV) [12], Temporally-Ordered Routing Algorithm (TORA) [11], Wireless Routing Protocol (WRP) [10] and the DARPA packet radio protocol. However, these algorithms do not take node or network life into consideration, as a result of which, a small set of nodes may be overused and their energy resources quickly exhausted. For instance, in Fig. 1, shortest-hop routing will route packets between 1-4, 2-5 and 3-6 via node 0, causing the node to die relatively early [15].

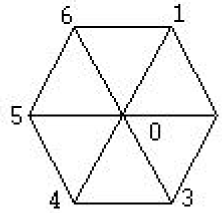

Fig. 1: A network illustrating the problem with shortest hop or minimum energy as the cost metric.

Power-aware routing is one of the more recent cost metrics for ad-hoc networks and the most popular algorithms in this field include Power-Aware Multi-Access Protocol with Signaling (PAMAS) [14], Minimum Energy Mobile Wireless Networks [13] and Routing for Maximum System Lifetime (MSL) [2], [3], [4]. While the Minimum Energy Protocol aims at designing a network that consumes the minimum energy per unit flow of packet (which could still lead to a quick drain-out, as illustrated above), MSL uses a maximum residual energy path routing algorithm to maximize the time until any node failure. Thus the objective of the algorithm being reviewed is to maximize the lifetime of the system, instead of minimizing the consumption of energy. The authors identify the problem as a linear programming problem, as has been discussed in Section II and the results tabulated. Finally, Section III looks at alternative power conservation techniques that exist in the literature, and concludes the study with a few suggestions for furthering the scope of the paper.

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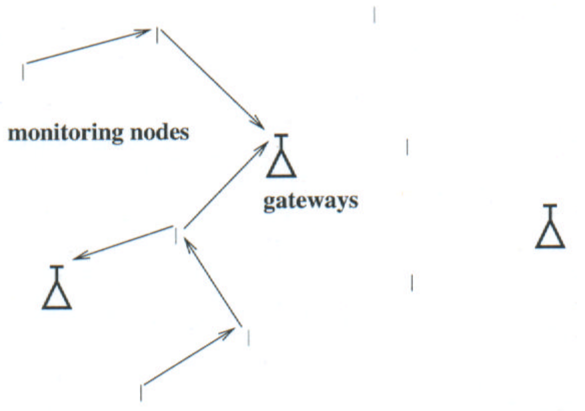

Fig. 2: A multi-hop wireless ad-hoc network in which information generated at the randomly distributed monitoring nodes has to be delivered to the gateway nodes. [4]

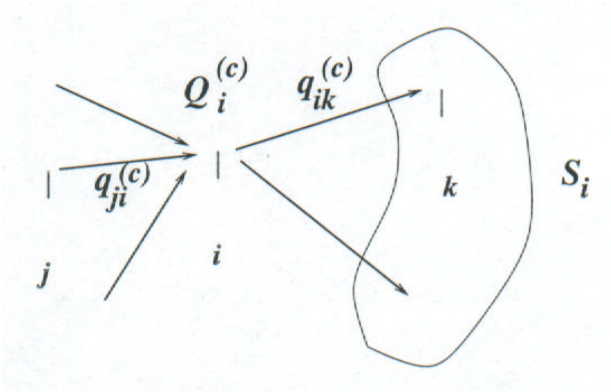

Fig. 3: The conservation of flow condition at node *i* requires that the sum of information generation rate and the total incoming rate must equal the total outgoing flow. [4]

II. MAXIMUM SYSTEM LIFETIME ROUTING

Early research in ad-hoc networks ignored the aspect of energy efficiency. However, since mobile nodes are typically small and portable [9], it imposes stringent constraints on the battery size and power. As a node sends, receives or forwards packets, the energy of the node is decremented accordingly, and once the energy level falls below a threshold, it suffers a complete shutdown. Since the ad-hoc routing protocol determines which nodes will forward the packets, the type of protocol being used will affect the energy performance of the system in two important ways— first, the routing overheads affect the amount of energy used for sending and receiving the routing packets, and second, the chosen route affects which nodes will have a faster decrease of energy.

The authors propose an algorithm [4] that selects routes so that the time until the batteries of the nodes drain out is maximized. In order to maximize the lifetime, traffic is routed such that the energy consumption is balanced among the nodes in proportion to their energy reserves, instead of routing to minimize the absolute consumed power. The paper being reviewed is a culmination of a number of years of research, and the intermediate publications [2], [3] describing the development of the work have also been incorporated into this assessment.

A. Problem Formulation

Chang and Tassiulas consider a group of wireless static nodes randomly distributed in a region as in Fig. 2, where each node has a limited energy supply (for instance, a battery). Each node generates information that needs to be delivered to some nodes designated as gateway nodes. As mentioned before, the wireless nodes are assumed to have the capability of packet forwarding, *i.e.* relaying an incoming packet to one of its neighboring nodes, and the transmit power level can be adjusted to a level appropriate for the receiver to be able to receive the data correctly if the receiver is within transmission range. The algorithm should also avoid the problem illustrated in Fig. 1, *viz.* a well-positioned node should not have all the traffic directed through it.

B. Problem Analysis

Define
N: set of all nodes
O: set of origin nodes
D: set of destination nodes
S_i: subset of D that can be reached by node i
q_{ij}: flow rate of data transmission from node i to j
e_{ij}: energy required to transmit one bit from i to j
Q_i: rate at which information is generated at node i
E_i: initial battery energy of node i

Then, the lifetime of node *i* under a given flow $\mathbf{q}=\{q_{ij}\}$ is given by:

$$T_i(\mathbf{q}) = \frac{E_i}{\Sigma\, e_{ij}\ \Sigma\, q_{ij}}$$

The system lifetime under flow **q** may be defined as the length of time until the first battery drain-out among all nodes in N, which is the same as the minimum lifetime over all nodes, *i.e.*

$$T_{sys}(\mathbf{q}) = \min T_i(\mathbf{q})$$
$$= \min \frac{E_i}{\Sigma\, e_{ij}\ \Sigma\, q_{ij}}$$

The goal is to find the flow that maximizes the system lifetime (T_{sys}) under the flow conservation condition. Thus, the objective may be written as:

$$\max_{q} \quad \min_{i \varepsilon N} \quad \frac{\underline{E_i}}{\Sigma e_{ij} \Sigma q_{ij}}$$

i.e. the lifetime of a system under flow q is defined as the minimum battery lifetime over all nodes and this lifetime is maximized by choosing the appropriate flow.

This can be solved as a linear programming problem [5], where the conditions for the optimization problem are:

$$q_{ij} \bullet 0$$

$$\bullet \; q_{ji} + Q_i = \bullet \; q_{ik}$$

In [3], the authors made use of a theorem based on the necessary optimality condition, from which the routing algorithm follows. The theorem states that if the minimum lifetime over all nodes is maximized, then the minimum lifetime of each path flow from the origin to the destination with positive flow has the same value as the other paths. The Maximum Residual Energy Path Routing algorithm was applied after this. The basic idea behind this algorithm is to route packets through paths that have the maximum residual energy so that energy consumption in all paths will be balanced.

Define

P_i: set of all paths from node *i* to destination node *d*

Lp: path length vector whose elements are the reciprocal of the residual energy for each link in the path after the route has been used for a unit flow

i.e., for link (j, k),

$$L_p = [\ E_j - e_{jk}\ \hat{u}\ ]^{-1}$$

where E_j is the residual energy at node *j* and û is a unit flow.

By using the lexicographical ordering in this case by comparing the largest elements first and so on, the shortest path from each node i to the destination was then obtained using a slightly modified version of the distributed Bellman-Ford algorithm [1]. Thus lifetime is maximized by routing traffic in such a way that the energy consumption is balanced among nodes in proportion to their energy reserves, instead of routing to minimize the absolute consumed power.

However in [4], the paper currently under review, the authors use a slightly different approach to obtain the Maximum System Lifetime routing algorithm. Their objective is to find the best link cost function that would lead to the maximization of the system lifetime. The three parameters being considered to calculate the cost function c_{ij} for link (*i*, *j*) are— the energy expenditure for unit flow transmission (e_{ij}), the initial energy (E_i) and the residual energy at the transmitting node *i* ($\underline{E}_i$).

With the above in mind, the link cost c_{ij} is proposed to be

$$c_{ij} = e_{ij}^{x1}\ \underline{E}^{-x2}\ E^{x3}$$

A good candidate for the flow-augmenting path should consume less energy and should avoid nodes with small residual energy since the minimum lifetime of all nodes has to be maximized. The parameters *x1*, *x2* and *x3* above should be chosen such that the energy expenditure term is emphasized when the nodes have plenty of residual energy and the residual energy term becomes emphasized when the residual energy becomes small. As before, the path cost is computed by the summation of the link costs on the path, and the algorithm can be implemented with any existing shortest path algorithms, including the distributed Bellman-Ford algorithm [1]. The authors call this the Flow Augmentation (FA) algorithm and represent it as FA[x1,x2,x3].

Table I: PERFORMANCE COMPARISON OF DIFFERENT ROUTING ALGORITHMS IN SINGLE-COMMODITY (S.C.) AND MULTI-COMMODITY (M.C.) CASES

ALGO-RITHM X	AVG. R_X		MIN. R_X		PR{R_X>0.9}	
	S.C.	M.C.	S.C.	M.C.	S.C.	M.C.
FA[1,50,50]	.9985	.9974	.9911	.9906	100%	100%
FA[1,1,1]	.9744	.9565	.7347	.7178	94%	86%
MREP	.9572	.9349	.8110	.7298	89%	69%
MTE	.7310	.6982	.1837	.2201	33%	25%

The authors also extend their work from [3] and propose an extension of the Flow Redirection (FR) algorithm for the multi-commodity case, which includes not only the case of a single origin and single destination, but also multiple origins and destinations (without any constraint on the information generation results). It can be proved (by contradiction) that regardless of the scenario, under optimum flow, the minimum lifetime of every path from the origin to the destination with positive flow is the same. If for instance, the minimum lifetimes of the paths with positive flow were not all identical under an optimal flow condition, then there would be atleast one path with positive flow whose minimum lifetime would be the shortest. Thus, the minimum lifetime of this path (which is also the system lifetime) could be increased by simply redirecting an arbitrary amount of flow to the paths whose lifetime is longer than this path such that the minimum lifetime of the latter path is still longer than the system lifetime before redirection, which contradicts the optimal flow assumption.

In the FR algorithm, a portion of each commodity flow at every node is redirected in such a way that the minimum lifetime of every path with positive flow from the node to the destination will increase (or atleast remain the same).

C. Simulation Results

In order to analyze the performance of different routing algorithms, the authors define a function denoted by R_X, which indicates the performance of algorithm *X*. R_X is defined as the ratio of the maximum system lifetime obtained using algorithm *X* to the optimum system lifetime.

Table I summarizes the results of the simulation. The authors compare the results of the maximum system lifetime (MSL) routing algorithm (using fa[1,1,1] and fa[1,50,50]) with that of the minimum transmitted energy (MTE), as well as the maximum residual energy path (MREP), proposed in [3] by simulating 200 randomly generated graphs. The average gain in the system lifetime obtained by the proposed algorithms was between 40% and 62% compared with MTE.

It should be pointed out that the authors make a distinction between single-commodity and multi-commodity cases. The former was for the scenario where information generated at five origin nodes needed to reach any of two destination nodes, whereas in the multi-commodity case, each of the five origin nodes has its own single designated destination node.

III. CONCLUSION

The idea forwarded by Chang and Tassiulas in this paper is one of those that appear misleadingly simple, although simplicity is the least of its virtues. The authors' papers on energy conservation [2], [3], [4] have been instrumental in influencing a lot of research in power-aware routing algorithms in the recent past. For instance, this paper formed the basis for Li, Aslam and Dus' [8] work on online power-aware routing in large wireless ad-hoc networks for applications where the message sequence is not known. This differs from [4] in defining the lifetime of the network with respect to a sequence of messages as the earliest time when a message cannot be sent due to saturated nodes. On the other hand, Feeney and Nilsson [6] have criticized the approach of using sensors to cooperatively forward sampled data to more powerful hosts as "abstract" and have objected to the treatment of energy as a "commodity" [*ibid.*]. They perform a series of experiments to obtain energy consumption measurements in an IEEE 802.11 ad-hoc network environment, and present the data as a collection of linear equations for calculating energy at different points. This, they claim, provides a solid experimental basis for energy-aware design and evaluation of network-layer protocols, including several "subtle" issues commonly overlooked in theory and simulations.

Mention must also be made of Singh, Woo and Raghavendra [15] who arrived at a similar conclusion as Chang and Tassiulas with respect to power-aware routing in mobile ad-hoc networks. While not as mathematical as [4], the authors suggest that the key to choosing the optimum metric for power conservation (*i.e.* to increase individual node and hence, network life) is to carefully share the cost of routing packets. In order to maximize the time until network partition (which is what Chang and Tassiulas' algorithm would do if there were no network redundancy), a load-balancing concept is applied, which attempts to evenly distribute routing through critical nodes, an early death of which will cause the network to partition.

In conclusion, maximum system lifetime routing for ad-hoc networks successfully introduces a new paradigm of power-conservation routing in which the routing decision is governed by the amount of residual energy in neighboring nodes. A possible drawback is that the authors consider only two classes of nodes in their analysis— static monitoring nodes and static gateway nodes— and therefore there is scope to introduce more classes, in particular mobile nodes, for completeness.

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