Energy Efficient Routing in Wireless Ad Hoc Networks

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***Abstract*—Ad hoc wireless networks are power constrained since nodes operate with limited battery energy. Thus, energy consumption is crucial in the design of new ad hoc routing protocols. To design such protocols, we have to look away from the traditional minimum hop routing schemes. In this paper, we propose three extensions to the state-of-the-art shortest-cost routing algorithm, AODV. The discovery mechanism in these extensions (LEAR-AODV, PAR-AODV, and LPR-AODV) uses energy consumption as a routing metric. They reduce the energy consumption of the nodes by routing packets to their destination using energy-optimal routes. We show that these algorithms improve the network survivability by maintaining the network connectivity. They carry out this objective with low overhead and without affecting the other wireless network protocol layers.**

Keywords-ad hoc routing, energy consumption, network survivability, AODV.

I. Introduction

The increasing progress of wireless local area networks (WLAN) has opened new horizons in the field of telecommunications. Among the various network architectures, the design of mobile ad hoc network (MANET) has attracted a lot of attention. A MANET is composed of a set of mobile hosts that can communicate with one another. No base stations are supported in such an environment, and mobile hosts communicate in a multi-hop fashion. Such networks are needed in situations where temporary network connectivity is required, such as in battlefields, disaster areas, and meetings, because of their capability of handling node failures and fast topology changes. Those networks provide mobile users with ubiquitous communication capability and information access regardless of location.

A set of ad hoc routing protocols have been proposed in the IETF's MANET [1] group to ensure the network connectivity. They operate in either proactive or reactive modes. Proactive protocols are table-driven and maintain routes for the entire network. Nodes must be in continuous communication for updating changes in the topology. In reactive protocols, a route to a destination is established only on demand, based on an initial discovery between the source and the destination.

Building such routing algorithms poses a significant technical challenge, since the devices are battery operated. The devices need to be energy conserving so that battery life is maximized. The shortest path is the most common criteria adopted by the conventional routing protocols proposed in the MANET Working Group. The problem is that nodes along shortest paths may be used more often and exhaust their batteries faster. The consequence is that the network may become disconnected leaving disparity in the energy, and eventually disconnected sub-networks. Therefore, the shortest path is not the most suitable metric to be adopted by a routing decision. Other metrics that take the power constraint into consideration for choosing the appropriate route are more useful in some scenarios (e.g. sensor networks).

In this paper, we propose three energy efficient routing algorithms (LEAR-AODV, PAR-AODV, and LPR-AODV) that reduce energy consumption and lead to a longer battery life at the terminals. They are based on one of the most important routing protocols, AODV (Ad hoc On-Demand Distance Vector) [2]. We focus on reactive routing schemes, since they are less expensive in terms of energy consumption than proactive schemes [3].

The remainder of this paper is organized as follows. We detail the different energy efficient routing algorithms we propose in section 2. Performance evaluation and numerical results are exposed in section 3. Finally, section 4 summarizes the main contributions of this work.

II. Energy Efficient Routing Algorithms

In this section, we present new energy efficient routing algorithms. They are designed to increase the network survivability by maintaining the network connectivity and to lead to a longer battery life of the terminals. This is in contrast to AODV which does not consider power but optimizes routing for lowest delay. The protocols we developed (LEAR-AODV, PAR-AODV, and LPR-AODV) ensure the survivability of the network by establishing routes that ensure that all nodes equally deplete their battery power. They are reactive protocols and are based on the AODV routing protocol described below.

A. *AODV Protocol*

AODV routing protocol [2] is a reactive routing algorithm. It maintains the established routes as long as they are needed by the sources. AODV uses sequence numbers to ensure the freshness of routes. Route discovery and route maintenance for AODV are described below.

A.1. Route Discovery

The route discovery process is initiated whenever a traffic source needs a route to a destination. Route discovery typically involves a network-wide flood of route request (RREQ) packets targeting the destination and waiting for a route reply (RREP). An intermediate node receiving a RREQ packet first sets up a reverse path to the source using the previous hop of the RREQ as the next hop on the reverse path. If a valid route to the destination is available, then the intermediate node generates a RREP, else the RREQ is re-broadcast. Duplicate copies of the RREQ packet received at any node are discarded. When the destination receives a RREQ, it also generates a RREP. The RREP is routed back to the source via the reverse path. As the RREP proceeds towards the source, a forward path to the destination is established.

A.2. Route Maintenance

Route maintenance is done using route error (RERR) packets. When a link failure is detected, a RERR is sent back via separately maintained predecessor links to all sources using that failed link. Routes are erased by the RERR along its way. When a traffic source receives a RERR, it initiates a new route discovery if the route is still needed. Unused routes in the routing table are expired using a timer-based technique.

B. Local Energy-Aware Routing based on AODV (LEAR-AODV)

The first on-demand routing protocol we propose is called LEAR-AODV (Local Energy-Aware Routing based on AODV). The main objective is to balance energy consumption among all participating nodes. We use a similar mechanism to that used in [2], where the authors propose to extend the DSR (Dynamic Source Routing) [4] protocol. In their approach, each mobile node relies on local information about the remaining battery level to decide whether to participate in the selection process of a routing path or not. An energy-hungry node can conserve its battery power by not forwarding data packets on behalf of others. The decision-making process in LEAR-AODV is distributed to all relevant nodes. Route discovery and route maintenance for LEAR-AODV are described below.

B.1. Route Discovery

In AODV, each mobile node has no choice and must forward packets for other nodes. In LEAR-OADV, each node determines whether or not to accept and forward the RREQ message depending on its remaining battery power (E_r). When it is lower than a threshold value θ ($E_r \leq \theta$), the RREQ is dropped; otherwise, the message is forwarded. The destination will receive a route request message only when all intermediate nodes along the route have enough battery levels.

B.2. Route Maintenance

Route Maintenance is needed either when the connections between some nodes on the path are lost due to node mobility, or when the energy resources of some nodes on the path are depleting too quickly. In the first case, and as in AODV, a new RREQ is sent out and the entry in the route table corresponding to the node that has moved out of range is purged. In the second case, the node sends a route error RERR back to the source even when the condition $E_r \leq \theta$ is satisfied. This route error message forces the source to initiate route discovery again. This is a local decision since it is dependent only on the remaining battery capacity of the current node.

However, if this decision is made for every possible route, the source will not receive a RREP message even if there exists a route between the source and the destination. To avoid this situation, the source will re-send another RREQ message with an increased sequence number. When an intermediate node receives this new request, it lowers it's θ by d to allow the packet forwarding to continue. We use a new control message, *ADJUST_Thr*. When a node drops a RREQ message, it instead broadcasts a *ADJUST_Thr* message. The subsequent nodes closer to the destination now know that a request message was dropped and lower their threshold values. Now, the second route request message can now reach the destination. When the destination receives a RREQ, it generates a RREP. As in AODV, the RREP is routed back to the source via the reverse path.

We notice that LEAR-AODV interworks easily with AODV. By this, we mean that an ad hoc network can contain both nodes carrying out LEAR-AODV, and nodes carrying out AODV as routing protocol.

C. Power-Aware Routing based on AODV (PAR-AODV)

The second on-demand routing protocol we propose is called PAR-AODV (Power-Aware Routing based on AODV). The main objective is to extend the useful service life of an ad hoc network. PAR-AODV solves the problem of finding a route π, at route discovery time t, such that the following cost function [6] is minimized:

$$C(\pi, t) = \sum_{i \in \pi} C_i(t) , \tag{1}$$

where $$C_i(t) = \rho_i \left(\frac{F_i}{E_i(t)} \right)^{\alpha} \tag{2}$$

and ρ_i is the transmit power of node i;

F_i is the full-charge battery capacity of node i;

$E_i(t)$ is the remaining battery capacity of node i at time t;

α is a positive weighting factor.

The route discovery and route maintenance for PAR-AODV are described below.

C.1. Route Discovery

In PAR-AODV, activity begins with the source node flooding the network with RREQ packets when it has data to send. All nodes except the source and the destination calculate their link cost, C_i, using (2), and add it to the path cost in the header of the RREQ packet (cf. (1)). When the destination node receives a RREQ packet, it sends a RREP packet to the source.

When an intermediate node receives a RREQ packet, it keeps the cost in the header of that packet as *Min-Cost*. If additional RREQs arrive with the same destination and sequence number, the cost of the newly arrived RREQ packet is compared to the *Min-Cost*:

- If the new packet has a lower cost and if the intermediate node does not know any valid route to the destination, *Min-Cost* is changed to this new value and the new RREQ packet is re-broadcast;

- If the new packet has a lower cost but the intermediate node knows a route to the destination, the node forwards (unicast) a *COMPUTE_Cost* message. The *COMPUTE_Cost* calculates this route cost;

- Otherwise, if the new packet has a greater cost, the new RREQ packet is dropped.

When the destination receives either a RREQ or a *COMPUTE_Cost* message, it generates a RREP message. The RREP is routed back to the source via the reverse path. This reply message contains the cost of the selected path. The source node will select the route with the minimum cost.

C.2. Route Maintenance

The route maintenance in PAR-AODV is the same as in LEAR-AODV. Hence, in PAR-AODV, when any intermediate node has a lower battery level than its threshold value ($E_r \leq \theta$), any request is simply dropped.

D. Lifetime Prediction Routing based on AODV (LPR-AODV)

The last on-demand routing protocol we propose is called LPR-AODV (Lifetime Prediction Routing based on AODV). This protocol favors the route with maximum lifetime, i.e. the route that does not contain nodes with a weak predicted lifetime. LPR-AODV solves the problem of finding a route π at route discovery time *t*, such that the following cost function is maximized:

$$\underset{\pi}{Max}\left(T_{\pi}(t)\right) = \underset{\pi}{Max}\left(\underset{i \in \pi}{Min}\left(T_i(t)\right)\right) \quad (3)$$

where $T_\pi(t)$ is the lifetime of path π;

$T_i(t)$ is the predicted lifetime of node *i* in path π.

LPR-AODV uses battery lifetime prediction. Each node tries to estimate its battery lifetime based on its past activity. This is achieved using a recent history of node activity. When node *i* sends a data packet, it keeps track of the residual energy value ($E_i(t)$) and the corresponding time instance (t). This information is recorded and stored in the node. After *N* packets sent/forwarded, node *i* gets the time instance when the N^{th} packet is sent/forwarded (t') and the corresponding residual energy value ($E_i(t')$). This recent history, $\{(t, E_i(t)), (t', E_i(t'))\}$, is a good indicator of the traffic crossing the node. Hence, we use it for lifetime prediction. Our approach is a dynamic distributed load balancing approach that avoids power-congested nodes and chooses paths that are lightly loaded. Route discovery and route maintenance for LPR-AODV are described below.

D.1. Route Discovery

In LPR-AODV, all nodes except the destination and the source calculate their predicted lifetime, T_i, using (4). In each request, there is another field representing the minimum lifetime (*Min-lifetime*) of the route. A node *i* in the route replaces the *Min-lifetime* in the header with T_i if T_i is lower than the existing *Min-lifetime* value in the header.

$$\mathrm{T_i(t)} = \frac{E_i(t)}{\mathrm{discharge\_rate}_i(t)} \quad (4)$$

where $\mathrm{discharge\_rate}_i(t) = \dfrac{E_i(t') - E_i(t)}{t - t'}$

and $E_i(t)$ is the remaining energy of node *i* at time *t*;

t: current time corresponding to the moment when the node *i* sends/forwards the current packet;

t': the recorded time instance corresponding to the moment when the N^{th} 'predecessor' to current packet was sent/forwarded by node *i*.

More precisely, when an intermediate node receives the first RREQ packet, it keeps the *Min-lifetime* in the header of that packet as *Min-Lifetime*. If additional RREQs arrive with the same destination and sequence number, the *Min-lifetime* of the newly arrived RREQ packet is compared to the *Min-lifetime*:

- If the new packet has a greater *Min-lifetime* and if the intermediate node does not know any valid route to the destination, *Min-lifetime* is changed to this new value and the new RREQ packet is re-broadcast;

- If the new packet has a greater *Min-lifetime* but the intermediate node knows a route to the destination, the node forwards (unicast) a *COMPUTE_lifetime* message. The *COMPUTE_lifetime* calculates this route lifetime;

- Otherwise, if the new packet has a lower *Min-lifetime*, the new RREQ packet is dropped.

When the destination receives either a RREQ or a *COMPUTE_lifetime* message, it generates a RREP message. The RREP is routed back to the source via the reverse path. This reply message contains the lifetime of the selected path. The source node will select the route with the maximum lifetime.

D.2. Route Maintenance

As in the first algorithms, route maintenance is needed either when a node becomes out of direct range of a sending node or there is a change in its predicted lifetime. In the first case (node mobility), the mechanism is the same as in AODV. In the second case, the node sends a route error RERR back to the source even when the predicted lifetime goes below a threshold level δ ($T_i(t) \leq \delta$). This route error message forces the source to initiate route discovery again. This decision depends only on the remaining battery capacity of the current node and its discharge rate. Hence, it is a local decision.

However, the same problem as in LEAR-AODV can occur. If the condition $T_i(t) \leq \delta$ is satisfied for all the nodes, the source will not receive a single reply message even though there exists a path between the source and the destination. To prevent this, we use the same mechanisms used in LEAR-AODV described above.

III. Experimental Results

The performances of our algorithms are evaluated using GloMoSim 2.0 simulator [8]. The simulation consists of a network of 36 nodes confined in a 800×800 m² area. Random connections were established using CBR traffic (at 4 packets/second with a packet size of 1024 bytes). The initial battery capacity of each node is 10 units. This initial energy is progressively reduced by data transmission/reception. When it reaches zero units, the corresponding node cannot take part any more in the communication, and is regarded as died. Each node has a radio propagation range of 250 meters and channel capacity was 2 Mb/s. We consider the simple case when the transmit power is fixed. In this case, each packet relayed or transmitted consumes a fixed amount of energy from the battery.

The performance metric, in these kind of studies, is the network lifetime. The network lifetime can be defined as [6]:

- the time taken for K nodes in the network to die;

- the time taken for the first node to die;

- the time for all nodes in the network to die.

In this work, we adopt the first and second definitions. Network lifetimes of our algorithms are compared for different scenarios. They are often compared to AODV since they are derived from it. Two cases were considered: (i) the nodes are fixed, and (ii) the nodes are mobile and move with various velocities.

A. Fixed Nodes

Figure 1 shows the time instances at which certain number of nodes has died because of their batteries depletion, when all the nodes are fixed. We note that for AODV, the first node dies approximately 2056 seconds earlier than in LEAR-AODV, 2572 seconds earlier than in PAR-AODV, and 3244 seconds earlier than in LPR-AODV. Similarly, and for 4 nodes, those die approximately 888 seconds earlier than in LEAR-AODV, 1132 seconds earlier than in PAR-AODV, and 1832 earlier than in LPR-AODV.

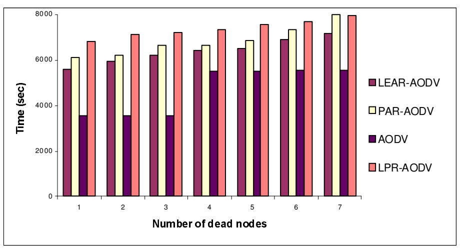
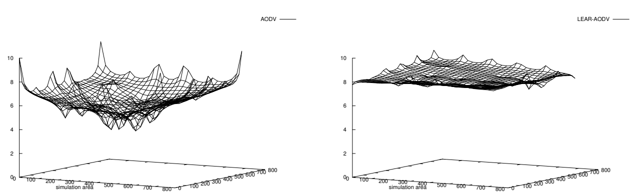


Figure 1. The number of dead nodes versus time.

LPR-AODV is better than PAR-AODV since LPR-AODV takes into account not only the residual battery capacity, but also the rate of energy discharge. We have carefully compared the performance of LPR-AODV for different values of N, and found *N*=5 to be a good value.



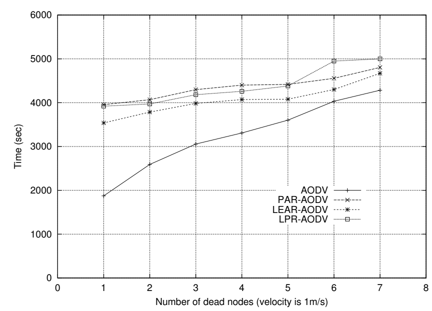
(a) (b)

Figure 2. Battery levels of all the ad hoc network nodes using (a) AODV (b) LEAR-AODV.

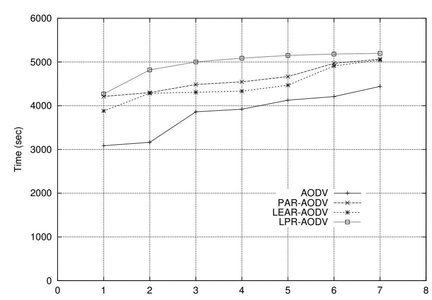
In order to improve the survivability of the network, the variance of energies between all the nodes should be reduced to the minimum. Figure 2 gives the battery levels of all ad hoc nodes after a total simulation time of 1000 seconds. We consider for this experiment that the nodes are fixed. We represent the results of LEAR-AODV (cf. Figure 2(b)), compared to those of AODV (cf. Figure 2(a)). In LEAR-AODV, the nodes consume energy more equitably. Thus, the nodes in the center of the network continue to maintain the network connectivity as long as possible, and the network will not be partitioned rapidly. On the other hand, for AODV, the energy level of the nodes in the center is largely lower than the half of the initial energy level.

B. Mobile Nodes

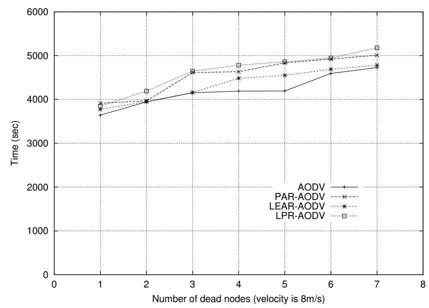
The effect of mobility is shown in Figure 3. As can be seen our algorithms are always better than AODV in terms of dead nodes. We note that for AODV, and for a node velocity equal to 4 meters/second for example, the first node dies approximately 793 seconds earlier than in LEAR-AODV, 1125 seconds earlier than in PAR-AODV, and 1182 seconds earlier than in LPR-AODV. However, as the velocity of the node movement increases, rate of energy consumption in the network goes up. This is normal since higher velocity of movement implies more route discoveries being performed and as a consequence higher energy consumption in the network. Also, as the node mobility increases, the difference between AODV and our algorithms decreases. Because there are more route discoveries, no paths are overused even by AODV. As a consequence, AODV also achieves load balancing to an extent decreasing the gain seen by our algorithms.



(a)



(b)



(c)

Figure 3. Number of dead nodes with a velocity of (a) 1m/s (b) 4m/s (c) 8m/s.

In these algorithms, route discovery process needs more control packets to be propagated in the network. To show the overhead of our algorithms, we have measured the ratio of the size of all the control packets to the size of all data packets delivered in the network. Figure 4 shows this ratio for our algorithms for different velocities of node movement, with a simulation time of 6000 seconds. As the velocity of movement increases, routes are valid for shorter time and more route discoveries are done in the network resulting in more control packets and more the difference between the algorithms.

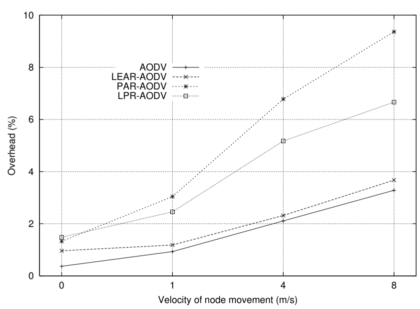


Figure 4. Bytes overhead as function of velocity of node movement.

IV. CONCLUSION

One critical issue for almost all kinds of portable devices supported by batteries is power saving. Without power, any mobile device will become useless. Battery power is a limited resource, and it is expected that battery technology is not likely to progress as fast as computing and communication technologies do. Hence, how to lengthen the lifetime of batteries is an important issue, especially for MANET, which is all supported by batteries.

Routing and power consumption are intrinsically connected. In conventional routing algorithms, which are unaware of energy budget, connections between two nodes are established through the shortest routes. These algorithms may however result in a quick depletion of the battery energy of the nodes along the most heavily used routes in the network.

In this paper, we design new power-aware routing protocols (LEAR-AODV, PAR-AODV, and LPR-AODV) that balance the traffic load inside the network so as to increase the battery lifetime of the nodes and hence the overall useful life of the ad hoc network. These protocols are based on the conventional AODV.

These AODV extensions increase the network survivability and lead to a longer battery life of the terminals. They achieve balanced energy consumption with minimum overhead. Simulation results show that our algorithms increase clearly network lifetime. Another important advantage of these algorithm is their simplicity and the fact that they do not affect other layers of wireless communication protocols.

REFERENCES

[1] IETF MANET WG (Mobile Ad hoc NETwork), www.ietf.org/html.charters/manet-charter.html.

[2] C. E. Perkins, E. M. Belding-Royer, and S. R. Das, “Ad hoc On-Demand Distance Vector (AODV) Routing”, *IETF Internet Draft*, draft-ietf-manet-aodv-13.txt.

[3] L. Ouakil, S. Senouci, and G. Pujolle, "Performance Comparison of Ad Hoc Routing Protocols Based on Energy Consumption", *Ambience Workshop 2002*, Torino, Italy, September 2002.

[4] D. B. Johnson, D. A. Maltz, Y.–C. Hu, “The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks (DSR)”, *IETF Internet Draft*, draft-ietf-manet-dsr-09.txt.

[5] K. Woo, C. Yu, D. Lee, H. Y. Youn, and Ben Lee, “Non-Blocking, Localized Routing Algorithm for Balanced Energy Consumption in Mobile Ad Hoc Networks”, *MASCOTS'01*, Cincinnati, Ohio, August 15-18, pp. 117-124, 2001.

[6] M. Maleki, K. Dantu, and M. Pedram, “Power-aware Source Routing in mobile ad hoc networks”, *Proceedings of ISLPED '02*, Monterey, CA, pp. 72-75, August 12-14, 2002.

[7] M. Maleki, K. Dantu, and M. Pedram, “Lifetime Prediction Routing in Mobile Ad Hoc Networks”, *IEEE Wireless Communication and Networking Conf.*, Mars, 2003.

[8] X. Zeng, R. Bagrodia, and M. Gerla, “GloMoSim: a Library for Parallel Simulation of Large-scale Wireless Networks”, *PADS'98*, Banff, Alberta, Canada, May 26-29, 1998.