LS-AODV: An Energy Balancing Routing Algorithm For Mobile Ad Hoc Networks

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Abstract—Battery-powered computing solutions have grown in importance and utility across a wide range of applications in the technology industry, including both consumer and industrial uses. Devices that are not attached to a stable and constant power source must ensure that all power consumption is minimized while necessary computation and communications are performed. WiFi networking is ubiquitous in modern devices, and thus the power consumption necessary to transmit data is of utmost concern for these battery powered devices. The Ad hoc OnDemand Distance Vector (AODV) routing algorithm is a widely adopted and adapted routing system for path finding in wireless networks. AODV's original implementation did not include power consumption as a consideration for route determinations. The Energy Aware AODV (EA-AODV) algorithm was an attempt to account for energy conservation by varying broadcast power and choosing paths with distance between nodes as a consideration in routing. Lightning Strike AODV (LS-AODV) described in this paper is a proposed routing algorithm that further accounts for energy consumption in wireless networking by balancing energy in a network. Quality of service is maintained while energy levels are increased through networks using the LS-AODV algorithm.

Index Terms—wireless sensor network, routing algorithm, energy balancing

I. Introduction

The exponential growth of computing device performance coupled with the ever shrinking of the size of devices has allowed computing to permeate nearly all places that people operate. As computers find ways into more devices, including items previously controlled by computers, the ability to communicate between devices using wireless communication has become practically required for all computing platforms. This has led to the concept of the ”Internet of Things” (IoT).

The concepts of IoT can be applied to a wide range of products and projects, including wireless communications in cars that enable use of Artificial Intelligence (AI) that “performs radio analytics, perceives the environment, and then takes optimal actions for different applications,” [1] low-bandwidth wireless networks for consumer products so as to not rely on a centrally-located internet-enabled router such as Amazon's Sidewalk [2], and the automatic monitoring of debris flow [3]. These networking applications would not be conductive to a central wireless routing solution as devices are likely to move around, and relying on a central routing device would likely be unreliable.

Devices in a centrally oriented network are assumed to remain largely stationary. The networking devices maintain a routing table with instructions on how to transmit data to any known device in the network. When adding the possibility of high mobility of the devices on a network, this central orientation is likely not reasonable. The concept of ”Mobile Ad hoc Networks” (MANET) account for these issues, where networks are “formed without any central administration” [4]. Algorithms for the routing of information through a MANET allow the designer to account for what are important concerns in the network in which the algorithm will be applied. If the nodes of a network are expected to be in constant movement, the routing tables for the networking devices will need to be able to constantly update their routing information as previously discovered routes are no longer valid and new paths become available. As more route-finding is needed to account for the movement of nodes, the increase in packets will consume more power. When nodes are connected to a constant power source, this may not be such a concern, and acceptable. For applications that use a limited power source such as a battery, the energy costs of constant route-finding must be addressed.

This report shall explain current on-demand routing algorithms, note their benefits and shortcomings, and then propose a new algorithm to address these shortcomings. Simulations testing the new and old algorithms are performed, and the results are examined.

II. Related Work

A. Ad-Hoc On-Demand Distance Vector

A verified solution to an ad-hoc network's routing needs is the Ad hoc On-Demand Distance Vector (AODV). This routing algorithm allows mobile nodes to dynamically determine a

path to a destination without needing to constantly maintain routes in a routing table. AODV can establish new pathways for packets to be sent toward a destination quickly and can hastily respond to link breakages and network topology changes [5]. However, one major downside of AODV is the lack of energy awareness throughout a network of battery-operated nodes.

During a transmission, a node will check its routing table to see if it has a "fresh" route to an intended destination. If one exists, then the data is transmitted toward a next-hop neighbor associated with the destination node. However, if no route exists, or the route has expired, the *route discovery* phase begins.

During route discovery, two types of packets are used to solidify the needed route: Route Request (RREQ) packets and Route Reply (RREP) packets. Initially when a node needs to find a route, RREQ packets are broadcasted to its neighbors containing a RREQ sequence number to help eliminate loops, a hop count, the source and destination address and sequence numbers signifying the newness of the request. Each neighbor that receives the RREQ can do one of two things: rebroadcast the message to its neighbors, or reply to the sending node with an RREP if the receiver has a valid entry to the destination in its own routing table. If the former is true however, the receiving node will increment the hop count of the packet, store the sending node's routing information in its own routing table, and broadcast the packet to its own neighbors. This process repeats for every subsequent node that does not have a valid route or until the destination itself is reached. Loops are avoided during this process by utilizing the RREQ sequence number and destination address combination. When the same combination of sequence number and destination address are encountered, the RREQ packet is dropped.

When either the destination node receives a RREQ intended for it, or a node has a fresh enough route to the destination in its routing table, a RREP packet is generated. This packet is then unicasted from the destination node, to the originating node that began the route discovery process. The RREP packet contains the hop count of the destination, plus the destination and source addresses and sequence numbers. As well, each intermediate node stores the routing information of the destination node on reception of the RREP packet.

In addition, routing errors can occur and are handled dynamically in AODV. The Route Error (RERR) packet is used to notify a source node of a broken link in the network. When a neighbor of any node is encountered that is not reachable, an RERR packet is generated and unicasted to the source node. This allows the originating device to respond quickly and attempt another route discover phase to find the intended destination. This makes AODV capable to handling mobile nodes in a wireless network [5].

Friis' 1946 paper [6] described "[a] simple formula for a radio circuit." In his paper, Friis described the relation between power received and power transmitted as:

$$\frac{P_R}{P_T} = \frac{A_R A_T}{D^2 \lambda^2} \tag{1}$$

where:

P_R = Power received by antenna

P_T = Power transmitted by antenna

A_R = Effective area for receiving antenna

A_T = Effective area for transmitting antenna

D = Distance between antennas λ =

Wavelength of transmission

The relationship between the effective area and gain of the antenna can be stated as [7]:

$$A_E = \frac{\lambda^2}{4\pi} G \tag{2}$$

where G is the gain of the antenna.

Using equation (2) to substitute effective area for gain, the transmission power can be described as:

$$P_T = \frac{(4\pi)^2 D^2 P_R}{G_T G_R \lambda^2} \tag{3}$$

For the purposes of this paper, the transmission wavelength is assume to be 2.4 GHz

B. Energy Aware AODV

In their paper titled "Energy Aware AODV (EA-AODV) Using Variable Range Transmission", Nayek et al. [4] proposed a simple routing algorithm that accounts for the distance between nodes and adjusts the transmission power of each sending node. This reduction of transmission power of sending nodes to only the amount needed to reach the receiving node within the receiving node's minimum received power saves energy when compared to AODV's design.

The critical steps of the EA-AODV algorithm, as taken from the paper [4], are:

1) The originating node creates a RREQ which it broadcasts to its neighbors using a fixed transmitting power. 2) Route finding to the destination proceeds like AODV.
3) If a successful route to the destination is discovered, each of the RREP in the intermediary nodes will add the *X* and *Y* coordinates of the node unicasting the RREP.
4) After receiving the first RREP, the originating node is allowed to wait an arbitrary amount of time, allowing multiple paths to the destination to arrive, if they exist.
5) The originating node calculates the distance between itself and the node that sent the RREP using the coordinates sent in the RREP and its own. If multiple RREP are received in the allotted time, the originating node will calculate distances to each RREP node received.
6) The closest intermediary node is chosen and its coordinates are entered into the originating node's routing table.

7) Using the Friis transmission equation in free space, the required transmission power is determined, using a constant receiving power for the receiving node.
8) Payload is transmitted over route.
9) If the desired route is broken, steps 1-8 are repeated.

III. Proposed LS-AODV Algorithm

This paper proposes a new algorithm, Lightning Strike AODV (LS-AODV), that not only brings awareness to battery-operated device's energy, but modifies routing based on *energy pathways*. This enhances the entire network's lifetime, as opposed to looking only at energy conservation of each node individually. High-speed video of a ground-striking bolt of lightning shows that a lightning bolt may start with multiple arcs of energy spreading outward. Once a path to ground has been found, the other arcs tend to dissipate, and the rush of charge from the sky to the ground continues. As lightning finds the path of least electrical resistance to dissipate the charge imbalance, LS-AODV finds the path of greatest reserve power and transmits along this path.

LS-AODV reflects the same energy saving model as EAAODV, where radio transmission power is tuned to the distance of an intended neighbor. However, the primary difference between the two algorithms lies in how routing is affected due to network energy.

LS-AODV works by including the current energy level of a node, plus the accumulated energy of the nodes along the RREQ path from source to either an intermediate node or the destination as fields in the RREQ packet. Given this value and the number of hops, a device can determine the average energy level of the nodes along any given path. Since hazardous loops are eliminated during the RREQ process, distinct paths from source to destination will be created. Figure 1 shows 3 possible paths that could be created during a route request. Devices along each route, depending on traffic patterns, will vary in how much energy they contain. LS-AODV aims to distribute energy usage by choosing the path with the highest average energy per node which will help to increase the lifetime of the entire network.

The packet structure of the RREQ is the same as EA-AODV, except two additional fields are included with the current nodes X and Y coordinates: the current node's energy level and the accumulated energy of the RREQ path. When a destination node receives an RREQ that is intended for it, the device will

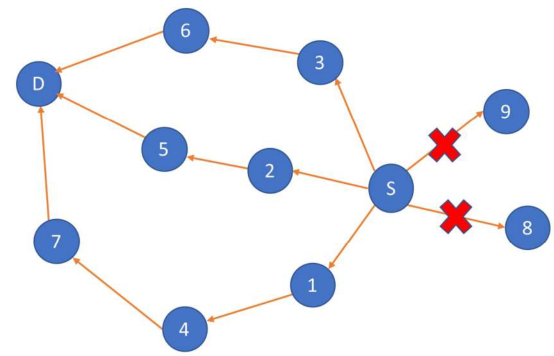

Fig. 1: Potential Route Request Paths to Destination.

wait a specified period of time, T_{RREQ}, to allow multiple RREQ messages to be received before sending a RREP. In traditional AODV, the first RREQ message triggers the route reply response, however for LS-AODV it is more important to conserve energy throughout the network than just sending a hasty reply. For each received RREQ from a specific originator device, the destination device will record the RREQ path with the highest average node energy. This is done by taking the accumulated energy field and hop number field:

$$\frac{\text{Accumulated energy}}{\text{hops}} = \text{Avg. Energy per node Num.}$$

Once the node has finished waiting for incoming RREQs, a RREP message will be sent to the neighbor that is associated with the highest average energy per node. The RREP process is then handled identically to traditional AODV.

Using the same network topology as in Figure 1, as an example, and using the initial energy levels of all nodes in Table I, the selection of a optimal energy path can be demonstrated.

Node Number	Initial Energy at time RREQ is received (J)
1	87
2	59
3	27
4	80
5	54
6	34
7	77
8	23
9	64

TABLE I: Initial Energy of Nodes in Joules.

Figure 2 shows node *S* broadcasting a RREQ to its neighbors in an attempt to reach node *D*. Just like in AODV, nodes that do not have an entry in their routing tables for device *D* will also broadcast RREQ messages to their neighbors. These nodes will also store an entry for *S* along with its Cartesian coordinates. Nodes 1, 2, 3, 8 and 9 that receive the first RREQ will then broadcast another RREQ with the same originator sequence number and address, but now with their own energy value added to the RREQ accumulated energy field.

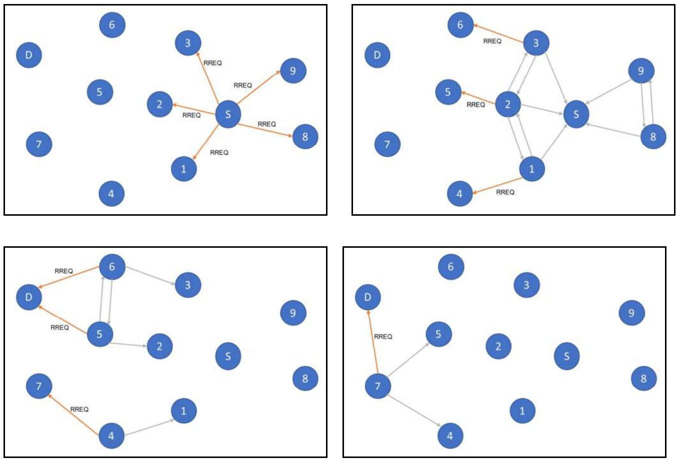

Fig. 2: RREQs broadcasted from Node *S* toward Node *D*.

The subsequent RREQs will propagate the same way as AODV, with the addition of each node adding its own current energy level to the RREQ packet. Once the destination, node *D*, receives the first RREQ from node *S*, it will start a timer for the specific sequence number and originator device address combination. Assuming that node 6 obtains the RREQ from node 3 first, node 5 from node 2 first, and node 4 from node 1 first, then node 7 from node 4 very shortly afterward, three distinct RREQ paths shown in Figure 1 will occur. The RREQ received at node *D* from node 6 will contain an accumulated energy value of 27 + 34 = 61 J while traveling from *S*→3→6→*D*. Keep in mind that the source and destination energy levels do not contribute to the energy value stored in the RREQ since they must be part of the transmission. The accumulated energy value from the RREQ from node 5 propagating through *S*→2→5→*D* would be 59+54 = 113 J and from node 7 through *S*→1→4→7→*D* would be 87+80+77 = 244 J.

Upon reception of each of these RREQs, the node *D* will take these values and divide by the RREQ hop count to determine the maximum average node energy level it had encountered up until that point. So for RREQs received through nodes 6, 5 and 7 the average node energy would be 30.5, 56.5 and 112, respectively. Node *D* will chose the path back to *S* through node 7 as its average energy per node is higher, despite the fact that the hop count is greater and most likely took longer to be received than the other RREQs (Figure 3). This return path for RREPs determines the route in which *S* will transmit to *D* for future transmissions.

Lastly, both the RREQ packets and the RREP packets contain the X and Y coordinates of the sending node. These coordinates are stored as part of a routing table entry for each node's neighbor. Energy savings occur for all unicasted messages (RREP, RERR and data transmission) in LS-AODV by reducing transmission power to just reach the node which the packet is destined for. Broadcasted messages (RREQs) are set to a default transmission range since RREQs are potentially used for the discovery of new neighbors in MANETs.

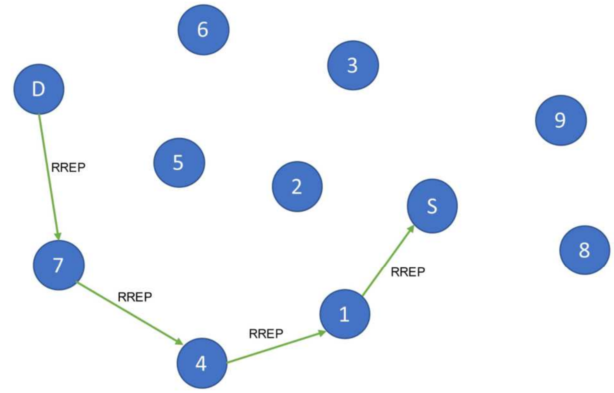

Fig. 3: RREP Return Path from Node *D* to Node *S*.

IV. Simulation and Results

LS-AODV was simulated using the open source networking simulation program "ns-3". According to its website, it is described as "a discrete-event network simulator for Internet systems, targeted primarily for research and educational use" [8].

ns-3 allows networking simulations of both wired and wireless networks. It includes a model of the AODV routing algorithm, which was used as the basis to build simulations of LS-AODV and EA-AODV for comparison.

To test the energy balancing of the two tested algorithms, a light-weight energy model was developed to work within ns-3. This energy model framework will be submitted to the ns-3 project to allow other researchers to use it in testing the energy implications of networking protocols and algorithms.

Three topologies were used in testing: 50, 75, and 100 nodes. For each of these three topologies, each node was randomly assigned coordinates distributed normally about both the *X* and *Y* axes. The plane of the topologies were a flat 250m x 250m square, with the (125, 125) point treated as the center of the plane. Figure 4 shows the 100 node topology.

Each node issued a packet sized 4096 bytes in size at one of four injection rates: 1, 2, 5, and 10 packets per second. Each packet was randomly assigned a destination node. The RREQ, RREP, and RERR packets were given a 64 byte size.

Each combination of topology and injection rate were tested, twelve in total, and tested on both LS-AODV and EA-AODV.

The Espressif ESP32 microcontroller with builtin WiFi capabilities was used as the model for power consumption in transmitting and receiving packets [9]. Each node in the simulations begin with 100 joules of energy, and each simulation runs for 10 simulated seconds. Nodes subtract from their energy level based on transmission power, receiving power, and idle timing, as dictated by the data sheet. When a node reaches zero power, it is considered dead and no longer transmits or is reachable by other nodes. If a node cannot reach other nodes due to intermediary nodes having died, it is also considered unreachable.

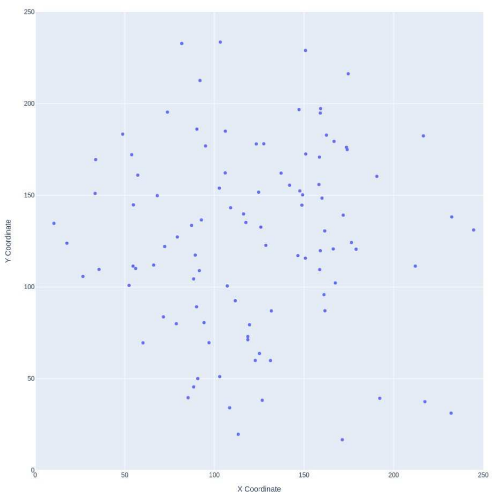

Fig. 4: 100 node topology

Table II shows the remaining amount of energy in each simulation for both EA-AODV and LS-AODV.

Nodes and Injection Rate	Energy Remaining(J) EA-AODV	Energy Remaining(J) LS-AODV	% More Energ Remaining in LS-AODV
50, 1pps	3287.97	3190.36	-2.97
50, 2pps	2401.02	2940.24	22.46
50, 5pps	1613.94	17.43.07	8.00
50, 10pps	882.22	1179.92	33.75
75, 1pps	4245.48	4603.86	8.44
75, 2pps	3142.97	3441.26	9.50
75, 5pps	1557.52	2026.99	30.14
75, 10pps	1098.51	1377.25	25.37
100, 1pps	1785.94	2396.61	34.19
100, 2pps	4253.51	4443.51	4.47
100, 5pps	2361.38	3081.83	30.51
100, 10pps	2103.09	2523.06	19.97

TABLE II: Energy Remaining in Networks.

Eleven of the twelve configurations show LS-AODV finishing with a higher amount of energy remaining in the network when compared to EA-AODV. Only the 50 node, 1 packet per second simulation shows more energy remaining in the EAAODV network, with LS-AODV with 3% less energy. For the remaining twelve, most LS-AODV networks have a double digit percentage points improvement, with a best performance in the 100 node, 1 packet per second network improving by 34.19%. Figure 5 shows the results of the 100 node 1 pps simulation for EA-AODV, and figure 6 shows the results for 100 node 1 pps in LS-AODV.

Table III shows the number of nodes remaining at the end of simulation that are still reachable. All twelve simulations show LS-AODV completing with more nodes still reachable than compared to EA-AODV.

V. Conclusion

Looking at the results of simulation, in both the total amount of energy remaining in each network and the number of nodes

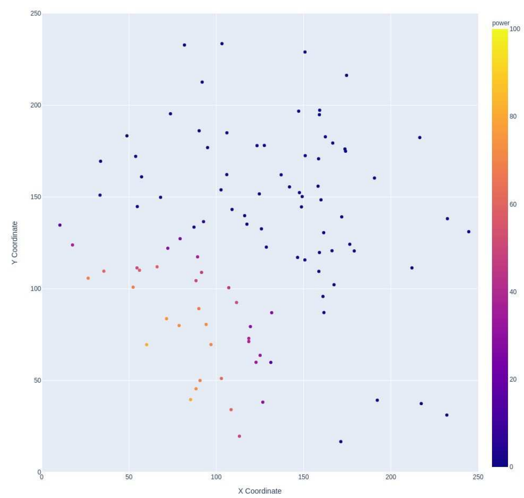

Fig. 5: 100 Nodes 1 PPS EA-AODV Simulation

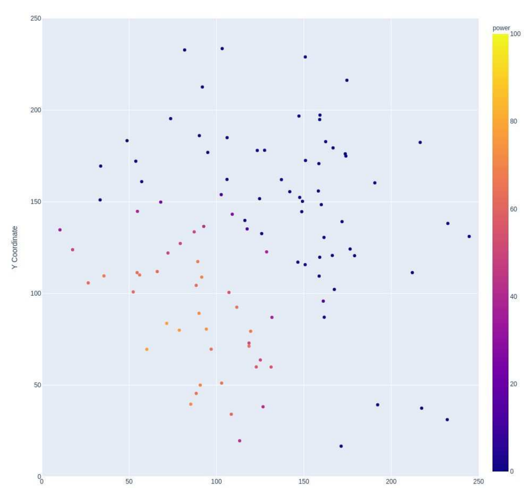

Fig. 6: 100 Nodes 1 PPS LS-AODV Simulation

still reachable at the end of simulation, LS-AODV has a substantial edge over EA-AODV in terms of balancing energy through a wireless network and improving network lifetime in networks that are constrained by battery limitations. Small computing devices with especially constrained batteries would likely benefit particularly well from LS-AODV. The easy to implement rules of LS-AODV allows it to be incorporated into any MANET that uses an AODV-based routing algorithm.

VI. Suggested Future Work

An idea to further improve the energy efficiency of LSAODV is giving intermediary nodes the option to receive multiple RREQ for a given route finding request and, if there is an option to either include another preceding node or to skip it, allow the intermediary node to decide whether skipping said node would increase the average energy of the path.

# Nodes and Injection Rate	EA-AODV	LS-AODV	Number More Nodes Reachable in LS-AODV
50, 1pps	45	47	2
50, 2pps	36	43	7
50, 5pps	26	28	2
50, 10pps	18	22	4
75, 1pps	61	69	8
75, 2pps	51	58	7
75, 5pps	32	37	5
75, 10pps	24	31	7
100, 1pps	38	47	9
100, 2pps	69	73	4
100, 5pps	44	54	10
100, 10pps	39	51	12

TABLE III: Number of Remaining Nodes in Networks.

In their paper, Hao et al. [10] proposed using energy criticality when routing data in a energy dependent networks. When a node reaches a defined low level of reserve energy, the node ceases to act of an intermediary node, only broadcasting data from itself and acting as a destination when requested. Such a scheme would be a welcome addition to LS-AODV.

The simulations for this paper were using nodes that were stationary. Running simulations or real-world experiments with nodes that move, and at different rates, would be very useful in understanding LS-AODV's impact on a MANET.

The initial broadcast range of the RREQ could use a ramping scheme, where a node starts broadcasting the RREQ at a low range which uses less energy, waits a prescribed time, and if no RREP is received, rebroadcast the RREQ with a higher transmission power. The repeating of RREQ broadcasts may result in more power consumption, but there may be certain network topologies where such a scheme on average reduces the power consumed in the RREQ phase of route finding.

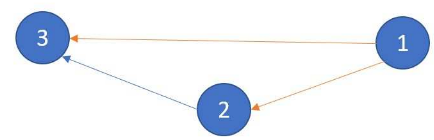

Fig. 7: Option to skip node 2

Figure 7 shows that node 1 can reach both nodes 2 and 3. Node 3 can be given the option to decide whether adding node 2 would increase the average energy in the path, or if node 1 should transmit directly to node 3.

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