Energy-Aware Algorithms for AODV in Ad Hoc Networks

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ABSTRACT

Energy efficiency is a critical issue for battery-powered mobile devices in ad hoc networks and routing based on energy-related parameters is used to extend the network lifetime. This paper presents a comprehensive energy optimized (locally and globally) routing algorithm and its implementation to AODV [1]. This algorithm investigates the combination of device runtime battery capacity and the real propagation power loss information, obtained by sensing the received signal power, without the aid of location information. The functions and messages provided by routing protocols (such as HELLO message and route discovery message) are utilized to embed the energy information. In particular, an adaptive low-battery alert mechanism is introduced to prevent overuse of critical nodes. Simulation results show that in both static and mobile networks, our algorithm can increase the network lifetime greatly based on first-dead time, average lifetime and most-dead time. Residual battery capacity deviation and range among nodes are also reduced. We conclude with a discussion for a trade-off issue between the network lifetime and network throughput.

Keywords: Wireless mobile ad hoc networks, AODV routing protocol, energy efficient routing, low-battery alert.

1 INTRODUCTION

In wireless ad hoc networks, each node functions as both a communication terminal and a router and due to mobility, it is usually battery-powered with wireless interfaces. For a large network, it is not desirable to recharge the battery for individual nodes, especially for such applications as sensor nodes in battlefields and hazardous environments. So the longevity of a node becomes a fundamental issue. There has been a good deal of research works in designing energy efficient protocols [1]. In this paper, we will focus on the energy efficiency issues in ad hoc routing, which deal with the parameters such as traffic load, battery capacity, and propagation characteristics in addition to the shortest path metric. Current literatures about energy efficient or power aware routing protocols can generally be divided into three categories: (i) switching on/off radio transmitters to conserve energy [2][3], (ii) power and topology control by adjusting the transmission range (power) of transmitters [4][5], and (iii) routings based on the energy-efficient metrics [6]-[11].

In the first approach, the radio is turned off for an adaptively varying period to save power when there is no traffic, since listening to the channel consumes significant power [2]. In order to adapt to operational environment, several algorithms are proposed, for examples, using application level information and node density [2], and routing fidelity and location information [3]. However, turning off the radio means more and faster network topology change. Routing uncertainty increases with more frequent routing update and extra routing messages, which can be severe in highly mobile networks.

Topology control is another approach, in which the transmission power is adjusted to achieve energy efficiency. For instance, in [4], by observing local and global topology information, the transmission power is changed while maintaining a connected topology. The node battery life is extended by using the radio's minimum power level. However, in sparse networks, there may be network partition and high end-to-end delay, while a dense network can cause limited spatial reuse and network capacity. In [5], a distributed power control scheme is proposed, in which power control level is established by exchanging control messages, according to the estimated minimum and maximum power level. There will be frequent link ups and downs, causing more link errors from MAC layer due to interference and unexpected channel collision. Retransmission due to link breakage will consume extra energy and network bandwidth.

For metric-based routing [6][7], different kinds of metrics are used to maximize the lifetime of networks by evenly distributing the energy consumption among all nodes. MBCR (Minimum Battery Cost) algorithm incorporates the battery capacity into the metric. In addition, the expected energy spent in reliably forwarding a packet over a specific link is considered in [8]. In order to maximize the network life time, the cost function defined in [9] takes into account energy expenditure for one packet transmission and available battery capacity. Furthermore in [10], the queue load condition and the estimated energy spent to transmit all packets in the queue are considered. The study of various battery discharging property and possible applications are presented in [11]. Idle time is introduced to the battery activity, which can help the charge recovery. However, due to the problems of routing protocols (discussed in section 3.2), critical nodes with very little battery capacity are not guaranteed to be protected. And most energy efficient algorithms are analyzed mathematically, and it becomes difficult to evaluate the performance with real routing protocols.

In this paper, a new energy efficient algorithm is proposed, which is readily implementable to current routing protocols such as AODV. This energy efficient extension is a metric-based algorithm, which integrates the runtime battery capacity and the estimated real propagation power loss, obtained from sensing the received signal power. So it is independent of location information and terrain-based, permitting power loss by terrain profiles such as large building blocks. Optimized cost functions are derived to combine the available information into one routing metric, which is optimized in two ways: local optimization among neighbor nodes and global optimization between end-to-end nodes. To protect critical nodes, an adaptive low-battery alert mechanism is introduced to force new route update. The algorithms are implemented into AODV in the simulations using OPNET. Performance in both static and highly mobile networks are studied, with different network topology and connectivity. Results show the average network lifetime in both static and mobile networks is significantly increased because energy consumption becomes evenly distributed.

In section 2, the algorithm details are discussed. In section 3, the implementation with AODV is presented with a routing protocol overview. Simulation results and performance evaluation are shown in section 4. Finally, we conclude the paper in section 5.

2 ENERGY OPTIMIZED ROUTING ALGORITHM

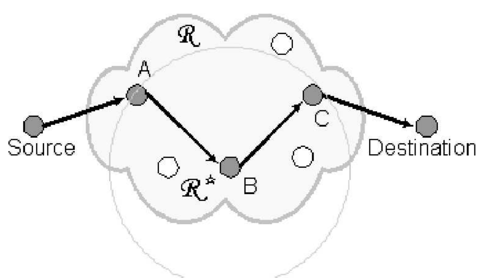

Figure 1: A multi-hop ad hoc network example, $\Re$ is the relay node set between source and destination $\Re^*$ is node B's immediate neighbor-node set.

Routing path selection based on the shortest path is usually not energy optimized. So different metrics are considered and weight is assigned to each link. Between two end-to-end nodes, there usually exists more than one route. In the potential relay node set, there will be relatively energy-optimal routes that can achieve the least cost based on the nodes' battery capacity and propagation loss of the links. In Fig. 1, we have a simple multi-hop network, with the relay node set $\Re$ between the source and destination, and the immediate neighbor set $\Re^*$ for each node. There exists an energy efficient route, for example, the route with relay nodes A, B, and C. Links with less propagation power loss and nodes with higher residual battery capacity are preferred. So the problem is simplified to minimize the power consumed during transmission and maximize the battery capacity of the next node to be used, that is to minimize:

$$\frac{p(i)}{g(i)} \qquad i \in \Re^* \tag{1}$$

for local (the immediate next hop) optimization

$$\sum_{i\in\Re} \frac{p(i)}{g(i)} \qquad i \in \Re \tag{2}$$

for global (all end-to-end hops) optimization

where *g(i)* is the residual battery capacity of the *i*th node, and *p(i)* is the power cost per packet from node *i*-1 to node *i* (that it, Joules per second per packet). A detailed study of the Lithium-Ion battery discharging property is presented in [12]. The voltage decrease and the battery capacity are non-linear functions of discharging time: the lower the capacity remains, the faster the battery voltage drops. The discharge curve and several battery cost functions related to battery capacity are discussed in [6] and [11].

The residual battery capacity can be evaluated as the amount of energy remains in the battery, that is, the time duration for the battery to discharge when the transmitter is consuming power. The residual battery capacity is reduced for the amount of energy consumed by the transmitter. If we define *f(i) = 1/g(i)* and expand *p(i)*, then (1) for local optimization will be

$$\frac{p(i)}{g(i)} = [p_{loss}(i-1,i) + p_{rx}(i) + p_c(i)] \cdot f(i) \tag{3}$$

where the power cost per packet *p(i)* from node *i*-1 to node *i* can be expanded to the sum of the power loss of this link (from node *i*-1 to *i*), the power cost to receive the packet at the *i*th node , and the power cost for routing messages to maintain this connection. The algorithm favors a link with less power loss and hence reduce the amount of energy consumed by potential re-transmission and link error. Usually the minimum threshold of receiving power of the receiver is constant (for instance, -80 dBm for current IEEE 802.11b cards) for all receivers (i.e, independent of the node index *i*). So the minimum value of $p_{rx}(i)$ can be set as a constant p_{rx}. Since the routing messages for route discovery and maintenance are the same for all nodes for on-demand routing protocols, we can consider $p_c(i)$ a constant value p_c too. Hence, both control and data packets are considered to consume energy according to their packet sizes. Note also that, when more link error occurs, more routing maintenance is needed and more energy is consumed. Therefore (3) can be expressed as

$$\frac{p(i)}{g(i)} = f(i) \cdot p_{loss}(i-1,i) + (p_{rx} + p_c) \cdot f(i) \tag{4}$$

Compare (4) with the function in [13], p_{cost} = $\alpha \cdot p_{loss}(i,j)$ + $\beta \cdot$ *f(j)*. We can see that α and β can be obtained by α = *f(i)*and β = p_{rx} + p_c, where β is a constant but the difference is that α is a variable depending on the battery capacity of the next forwarding node. Note that this algorithm is independent of location information. The value of propagation loss is obtained by calculating the difference between transmitting power and receiving power, which is determined by exchanging local routing control messages, such as HELLO message in AODV. So this value is relevant to the realistic propagation power loss under different channel conditions, not just the estimation from distance information.

This algorithm can either optimize locally for each hop or globally for the end-to-end route between a source-destination pair. Similarly, for global optimization, sum (4) along multi-hop routes:

$$\sum_{i \in \Re} \frac{p(i)}{g(i)} = \sum_{i \in \Re} [f(i) \cdot p_{loss}(i-1, i) + (p_{rx} + p_c) \cdot f(i)] \quad (5)$$

For the global optimization, the data source will get to know the summation of the cost for all possible routes and decide which route to choose, based on the global cost function (5). While for local optimization, each intermediate node will choose locally a different next hop to forward data for energy efficiency from the local cost function (4). Global optimization tends to prefer routes with fewer hops (because cost function (5) is a summation and is an implicit function of hop count) and hence can achieve less delay.

3 ENERGY OPTIMIZED AODV

AODV is selected as the baseline routing protocol because it is an on-demand protocol without global periodic routing advertisement. With small routing overheads, AODV consumes less overall network bandwidth and is scalable to large networks. With destination sequence number, AODV is loop-free and reliable. It can quickly respond to link breakage, and then repair routes with minor errors. HELLO message is used locally to maintain robust neighborhood connections by controlled flooding mechanism.

3.1 Ad hoc On-Demand Distance Vector (AODV) Routing Protocol

AODV [1] is an on-demand routing protocol, only when the source has data to send, a short route request (RREQ) message will be initiated and broadcast by the source, with an estimated and pre-defined lifetime (TTL). This RREQ is rebroadcast until the TTL reaches zero or an valid route is detected. The nodes receiving the RREQ will add a valid route entry to its routing table to reach the RREQ source, called reverse route formation. When the RREQ reaches the destination or a node that has a valid route to the destination, a route reply (RREP) message is uni-cast by this node to the source. If one round of route discovery fails (the RREQ TTL decreases to zero), the source will re-initiate a new RREQ with a larger initial TTL after time-out. If several rounds of route request all fail, it means no valid route can be found.

The RREP message will go to the source, following the reverse route formed by the RREQ. For every hop the RREP is forwarded, intermediate nodes will add a valid route pointing to the destination, called forward route formation, until the RREP reaches the source. If the RREP is generated by an intermediate node that already has a valid route to the destination, a special message called gratuitous route reply (G-RREP) is uni-cast to the destination, notifying it that the source has route request and then a bi-directional route is formed. By then, both the data source and destination have routes to each other, and all the intermediate nodes have routes to the source and destination. In the original AODV, source node will choose the shortest path if there are multi-routes discovered (with several route replies).

3.2 Algorithm Implementation with AODV

1) Enhanced HELLO Message: HELLO message is broadcast only one hop to maintain updated local connections. Energy information is embed to it so that neighbor nodes can have updated knowledge of the energy conditions of each other. To guarantee bi-directional links, we use RREQ message format as the HELLO and neighbor nodes receiving it will reply normally with a RREP to acknowledge this link. From the AODV specification [1], the following slight modifications are made:

a) HELLO RREQ format: The original 32-bit destination sequence number field is replaced with a new 32-bit value, obtained from the source battery function *f(s)*. Since destination address is the broadcast address, the destination sequence number does not perform any meaningful functions in HELLO RREQ. Fig. 2 shows part of the message format. The

0 …… 31 bit
……
Destination IP Address (Broadcast IP)
Source Battery Function Value *f(s)*
Source IP Address
……

Figure 2: HELLO RREQ message format.

new field *"Source Battery Function Value f(s)"* is calculated from the current residual battery capacity. For implementation, a counter indicating the remaining energy in the battery is used. Message length and other fields [1] are not changed.

b) HELLO RREP format: Reserved field (9 bits) in RREP message is used as *"Power Loss Level"* with 8 bits long, from the 10th to the 17th bit, shown in Fig. 3. This field is the

0 …			10		…				17		…	31 bit
…	7	0	1	2	3	4	5	6	7	0	1	2	3	…
…..		R	A	Power Loss Level									…..	

Figure 3: HELLO RREP message format.

power loss for a specific link, normalized to 8-bit long. The node that receives HELLO RREQ obtains the source battery function value *f(s)* and also the received signal power from the radio receiver. It is easy to calculate the power loss by subtracting the received signal power from the transmission power. the local optimization value will be calculated from the cost function based on these information and added to the local cost table. Then a RREP with energy information is unicast to the HELLO source, which can calculate the power loss and construct a new entry in its local cost table. By then, each node will have a local cost table with the cost to its neighbors.

2) Modification of RREQ/RREP for Global (end-to-end) Optimization: Global cost information travels along the full path when a route is being setup, and the end-to-end cost can be calculated and updated hop-by-hop from the global cost function (5), carried by a new 32-bit cost field in RREQ/RREP message. The backward global cost table is constructed during the route request, while the forward global cost table is formed during the route reply. Table 2 shows this process with an example discussed below.

The source initializes a RREQ with the global cost zero, and the nodes receiving it will find in their local cost table

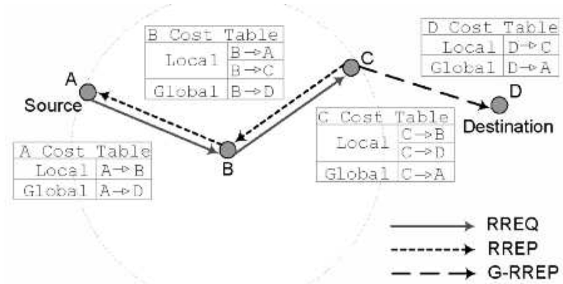

Figure 4: Route discovery in a four-node network scenario.

Table 1: Local cost tables constructed by HELLO.

Node	A	B	C	D
Local Cost Table	Cost(A→ B)	Cost(B→ A) Cost(B→ C)	Cost(C→ B) Cost(C→ D)	Cost(D→ C)

the local cost from themselves to the RREQ forwarder (indexed by IP address), and add this cost to the global cost in this RREQ. Then every time the RREQ is broadcast, each receiver will add the cost from itself to the previous forwarder to the global cost, called backward global cost formation (from relay nodes to the source).

When a RREP is generated by an intermediate node for this route discovery, the global cost is initialized to the cost from this node to the destination. Each node that receives this RREP will update the global cost field in the message by summing the value in this RREP with the local cost value from itself to the previous RREP forwarder. Then along the way the RREP is forwarded back to the source, all the relay nodes will update the global cost entry pointing to the destination in their global cost table, called forward global cost formation.

If a G-RREP is uni-cast to the destination, the global cost field is initialized with the value in the RREQ (the cost of this node to the source). When G-RREP is relayed to the destination, each relay node will also update its global cost field by summing the value in this G-RREP with the local cost from this node to the G-RREP forwarder. So the relay node will have the global cost to the source. This is still part of the backward global cost formation. After the whole process, the source knows the cost to the destination and vice versa, and all the intermediate nodes know the cost to both the source and destination. Global cost is kept valid until the route is outdated. For the simple scenario of Fig. 4, the local and the global optimization algorithms are described in table 1 and 2, respectively.

3) Adaptive Low-battery Alert Mechanism: Current on-demand routing protocols including AODV have a problem of overusing existing routes. Once a valid route is setup, before it is outdated, the source will be not able to discover newer and more efficient routes, although there may be better route available. The worst case is that under heavy load, if the network topology is not changing fast, the route discovered first will be overused and the nodes along this route will be drained out of energy rather quickly. To overcome this problem, we propose an adaptive low-battery alert mechanism to enforce new route update when relay nodes are drained below certain low-battery alert level, for example, 50% or 40% of the new battery capacity. To avoid excessive link breakage, this low-battery alert level is adjusted adaptively lower and lower. The

Table 2: Global cost table updated during route discovery.

	Node	Action	RREQ&(G-) RREP Cost	Global Cost Table
Backward global (D→ A) Cost Table	A	(A→ B) Broadcast RREQ	0	0
	B	(B→ C) Broadcast RREQ	Cost(B→ A)	0
	C	(C→ D) Uni-cast G-RREP	Cost(B→ A) +Cost(C→ B) =Cost(C→ A)	Cost(C→ A)
	D	Receiver G-RREP, update global cost table (D→ A)	Cost(C→ A) +Cost(D→ C) =Cost(D→ A)	Cost(D→ A)
Forward (A→ D) global cost table	C	(C→ B) Uni-cast RREP	Cost(C→ D)	Cost(C→ A)
	B	(B→ A) Forward RREP	Cost(C→ D) +Cost(B→ C) =Cost(B→ D)	Cost(B→ D)
	A	Receive RREP, update global cost table (A→ D)	Cost(B→ D) +Cost(A→ B) =Cost(A→ D)	Cost(A→ D)

first node that reaches its alert level will initialize a special route error (RERR) message for route update. Every time the alert level is reached, this alert level will be decreased by a small amount, called alert adjustment step, which reflects the willingness of a node to relay a data packet. The alert level is decreased uniformly, for example, 1% or 5% of the new battery capacity (actually, only crude measures of residual battery are practical). If a new efficient route is discovered, the routing protocol will use the new route, else the old route is used until a newly adjusted alert level is reached.

In the implementation with AODV, a special route error (RERR) message with local route repair function is generated when the alert level is reached, which means there are recoverable errors in the route. In AODV RERR message, when the 'N' bit is set to '1', whoever receives this RERR will not delete the current route entry, and just disable it to wait for the repairing of this route. The source will try to find a newer route if this RERR is received. Due to the new route update, there may be delay or even lost of data packets, and therefore will cause a little decrease of the network throughput.

4 SIMULATIONS

4.1 Simulation Environment

OPNET is used as the simulator, and all the simulations are based on 30 nodes randomly placed in a network of $1200 \times 500m^2$. The initial positions (coordinates) are uniformly distributed. Constant bit rate (CBR) data source is used, with a packet size of 4K bits every 0.25 or 0.1 seconds. 10 pairs of active data source and destination are randomly selected. In static networks, source and destination pairs are kept unchanged after randomly selected when the simulation is initialized. In mobile networks, the source and destination pairs are randomly chosen and communicate for 50 data packets, and the total number of pairs is kept constant at 10 pairs. Unfairness is eliminated because, for example, if a certain node is always chosen as a source, its own energy is mostly consumed by transmitting data packets, which has nothing to do with efficient routing. The mobility of nodes follows the random waypoint model, by which after the mobile node stays in one place for 60 seconds, a random direction and speed (0 - 20 meters/second) is chosen. The low-battery adjustment step is set at 1% of total power. Since the random seed defined in the simulation parameters controls the position and mobility, we use the same seed for all simulations in order to use the same network topology and mobility pattern to compare results.

In the simulations, our channel model is the free space propagation model. IEEE 802.11 peer-to-peer (ad hoc) mode is used at 1Mbps data rate. Default transmission range is 200 meters. The energy consumption model for the wireless interface is adopted from the specification of the 2.4GHz DSSS Lucent IEEE 802.11 WaveLAN PC cards [14]. Usually by constant 5 Volt, we assume 300 mA for transmitting and 250 mA for receiving. Given packet length in bits, power consumption can be calculated, for example, to transmit a packet of 4K bits including AODV header plus 224-bit IEEE 802.11 MAC header, the energy consumption is $5V \times 300mA \times (4 \times 1024 + 224)bits/10^6bps = 6.48 \times 10^{-3}$ Joules. The total battery capacity is assumed to be $1mA \cdot Hr$ for static nodes and $0.5mA \cdot Hr$ for mobile nodes for the sake of simulation time.

Several performance evaluation metrics are defined: *1) First-dead lifetime:* the time when the first node in the network dies (drained out of battery). *2) Most-dead lifetime:* the time when 70 percent of the nodes are dead. *3) Average network lifetime:* the average lifetime of the nodes died before the most-dead time. *4) Network throughput:* the total number of successful packets (bits) received at the destinations over the simulation time.

4.2 Simulation Results

1) Static Network Case:

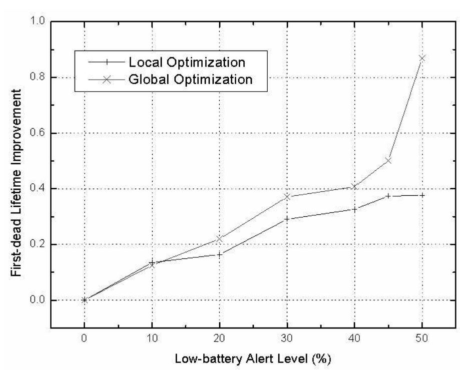

Figure 5: Static network *first-dead lifetime* improvement, with packet generation interval 0.25 seconds and transmission range 200 meters.

Since there is no network topology change, we only evaluate the first-dead lifetime because not all the nodes carry traffic. Fig. 5 shows the first-dead lifetime improvement compared with original AODV, with respect to different low-battery alert levels, from 0% to 50%. When the low-battery alert mechanism is disabled (level set to 0%), our algorithms show the same performance as the original AODV. This is expected because of the problem of current routing protocols as discussed in section 3. In static networks, unless link or node error occurs, current routing protocols will maintain the existing route throughout a session. That is exactly the reason why we introduce the low-battery alert mechanism. In Fig. 5, we observe that at 50% low-battery alert level, the first-dead lifetime increases 83% for global optimization and 39% for local optimization as compared to the original AODV. It is obvious that the sooner (i.e., the higher low-battery alert level) the low-battery alert algorithm applied, the longer lifetime the network could achieve.

2) Mobile Network Case:

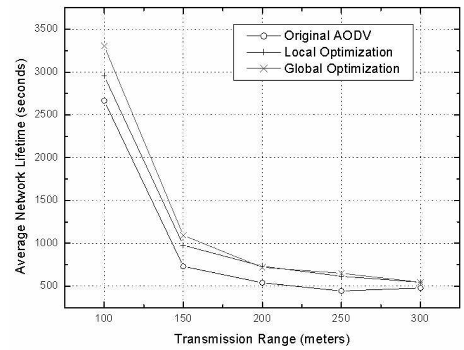

Figure 6: *Average lifetime* vs. transmission ranges, with packet generation interval 0.25 seconds, and low-battery alert level 50%.

Effect of Transmission Range: Average number of neighbor nodes can be changed by changing the wireless radio transmission range from 100 meters to 300 meters. As expected in Fig. 6, the network lifetime rapidly decreases as the transmission range becomes larger. When transmission range is 150 meters, our algorithms, by choosing energy efficient routes, can achieve up to 50% longer *average network lifetime* compared with the original AODV. The *average network lifetime* is mostly improved when the transmission range is from 150 meters to 250 meters, which interestingly coincides with the outdoor working range of IEEE 802.11 WLAN cards.

Effect of Low-Battery Alert Level: Transmission range is fixed at 150 meters, and packet generation interval is reduced to 0.1 seconds (heavy traffic load). Fig. 7 and 8 show the improvement on average network lifetime, the first-dead, and most-dead lifetime versus different low-battery alert levels. It is observed that by increasing the low-battery alert level, average network lifetime will also increase, consistent to the static case. When this level is low, local optimization algorithm performs better than global optimization, while global optimization is preferred when the low-battery alert level is high.

Usually local optimization can affect the real route condition faster than global optimization. Route decision is made

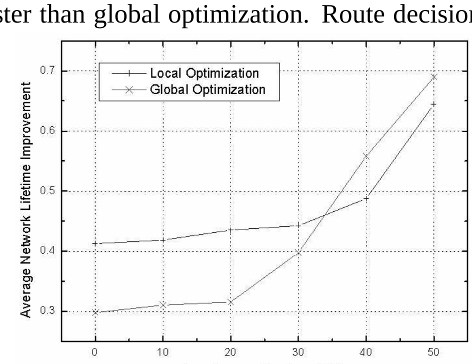

Figure 7: *Average lifetime* improvement with 150 meters transmission range, and packet generation interval 0.1 seconds.

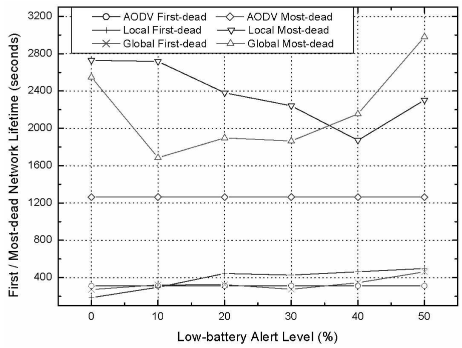

Figure 8: *First-dead time* and *most-dead lifetime* with 150 meters transmission range and packet generation interval 0.1 seconds.

each hop for local optimization, while for global optimization, only the source makes route decisions, which optimizes the route at a slower pace. So when the low-battery alert level is low, the global optimization may not have enough time to optimize the route before dead node occurs.

A trend is observed from Fig. 7-8: local optimization can achieve longer *first-dead lifetime* and *average lifetime* at a low-battery alert level up to 30%; while at high alert levels, up to 50%, global optimization can achieve better average lifetime. In case of the *most-dead lifetime*, both algorithms can improve up to over 2 times of the original AODV. It is noted that in Fig. 8, the *first-dead time* without low-battery alert is different from the static network case compared to AODV, because in static networks, there is no route update unless low-battery alerts occur, but in mobile networks, there are other kinds of route update, for example, link breakage due to node mobility can cause route updates. So without low-battery alert level, the critical nodes in the route can not be protected and the overuse-phenomenon may be more noticeable. That is why the *first-dead time* is even worse than original AODV.

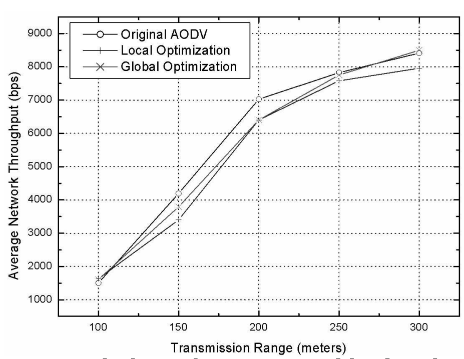

Figure 9: *Network throughput* averaged by low-battery alert levels, with packet generation interval 0.1 seconds.

Network Throughput: The expense of low-battery alert is the network throughput. Fig. 9 shows the *average network throughput* by different transmission ranges, and obviously the network throughput will be higher when nodes have larger transmission ranges. It is also interesting to observe that this increase is not linear, that is because when transmission range is increased, routes may become more robust and the average hop count may be fewer, but larger range also means more collision will occur in the shared wireless media. So the throughput increase is not proportional to the transmission range increase. It shows that the network lifetime is improved without affecting much the network throughput, when the low-battery alert level is under proper control. However, it is still a trade-off issue for the network lifetime and the network throughput.

5 CONCLUSIONS

We have discussed a new energy optimized algorithm that can be applied to current ad hoc routing protocols such as AODV. A cost function has been deduced based on both the propagation power loss and node battery capacity information and routes are optimized based on the cost functions of links and nodes. In particular, a low-battery alert mechanism is introduced to improve the routing update behavior, preventing overuse of critical nodes. Simulation results have shown that both local and global algorithms, easily implemented with AODV, can improve network lifetime in both static and mobile networks. Network throughput is not affected much, which is a trade-off issue with the low-battery alert level. The energy consumption is balanced among the network and the limited battery resources are utilized efficiently.

REFERENCES

[1] C. E. Perkins, E. M. Royer and S. R. Das, “Ad hoc On-Demand Distance Vector (AODV) Routing,” IETF RFC-3561, MANET Working group, 2003.

[2] Y. Xu, J. Heidemann and D. Estrin, “Adaptive energy-conserving routing for multihop ad hoc networks,” Technical Report TR-2000-527, 2000.

[3] Y. Xu, J. Heidemann and D. Estrin, “Geography-informed energy conservation for ad hoc routing,” Proceedings of the 7th Annual ACM Mobicom, 2001.

[4] Ramanathan and Rosales-Hain, “Topology control of multihop wireless networks using transmit power adjustment,” IEEE Infocom 2000, 2000.

[5] P. Bergamo, D. Maniezzo, A. Giovanardi, G. Mazzini, and M. Zorzi, “Distributed power control for power-aware energy-effi cient routing in ad-hoc networks,” Proceedings of European Wireless 2002 Conference, Feburary 2002.

[6] S. Singh, M. Woo and C. S. Raghavendra, “Power-aware routing in mobile ad hoc networks,” Proceedings of MobiCom 1998, 1998.

[7] C. K. Toh, “Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks,” IEEE Communication Magazine, 2001.

[8] Archan Misra, Suman Banerjee, “MRPC: Maximizing Network Lifetime for Reliable Routing in Wireless Environments,” IEEE Wireless Communications and Networking Conference (WCNC) 2002, March 2002.

[9] J. H. Chang and L. Tassiulas, “Energy conserving routing in wireless ad hoc networks,” IEEE Infocom 2000, March 2000.

[10] K. Kalyan kumar and A. Chockalingam, “Energy Effi cient Routing in Wireless Ad-hoc,” Proceedings of National Conference on Communications 2002, January 2002.

[11] Carla F. Chiasserini, Pavan Nuggehalli and Vikram Srinivasan, “Energy-Effi cient Communication Protocols,” Proceedings of 39th Design Automation Post-Conference (DAC) 2002, June 2002.

[12] Sean gold, “A PSPICE Macromodel for Lithium-Ion Batteries,” Proceedings of Annual Battery Conference on Applications and Advances, 1997.

[13] Ivan Stojmenovic and Xu Lin, “Power-aware localized routing in wireless networks,” IEEE Transactions on Parallel and Distributed Systems, 2001.

[14] Laura Marie Feeney and Martin Nilsson, “Investigating the energy consumption of a wireless network interface in an ad hoc netowkring environment,” IEEE Infocom 2001, April 2001.