An Energy-Aware Routing Mechanism for Mobile Ad Hoc Networks*

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Abstract

Most of the mobile ad hoc networks applications rely on battery-powered nodes. Thus, energy constraints are very important in this kind of network. This paper presents an energy-aware routing mechanism to balance the energy consumption among the nodes of the network. The mechanism was evaluated over the AODV protocol using a realistic energy consumption model. The energy model takes into account the way the packet is transmitted and the role-played by the node on its transmission. The results show that the packet length impacts the energy efficiency of the network and that the proposed mechanism increases the network lifetime from 13% for large packets to 19% for small packets, compared with the standard AODV protocol.

Key-words: Mobile ad hoc networks, energy management, network lifetime.

1 Introduction

The Mobile Ad hoc NETworks (MANETs) are composed by autonomous nodes capable of communicating without any previously installed infrastructure. This characteristic of the MANETs prevents any centralized administration. Thus, the ad hoc network is a complex distributed system where any node can act either as a connection end-user or as a router for the connections of other nodes. Therefore, the ad hoc routing protocols concentrate most of the research concerning MANETs.

There are two groups of ad hoc routing protocols, the pro-actives and the reactives. The pro-actives protocols aim to discover the network topology by exchanging periodical messages. The reactive protocols discover routes when a data packet needs forwarding. These protocols only achieve knowledge about part of the topology.

A critical factor on the ad hoc network operation is the energy consumption of its nodes. Typically, mobile nodes are battery-powered and the capacity of these batteries is limited by the weight and volume restrictions of the equipments. Consequently, it is important to reduce the energy consumption of the nodes. Moreover, since each node is a potential router, the failure of a node due to energy exhaustion may impact the performance of the whole network. Therefore, it is important to manage the energy consumption of all the nodes of the network.

Conventional ad hoc routing protocols use the hop-count as metric, but the utilization of energy-related metrics [1] is becoming common place. If we consider static ad hoc networks, the problem is simplified because one can discover the whole network topology. Wan et al. [2] address the problem referred to as "Minimum-Energy Routing". This problem consists of analyzing which route, in a given topology, would consume less total energy, and supposing the possibility of varying the transmission power of each node. Chang and Tassiulas [3] propose algorithms to balance flows among different routes, aiming to maximize the time needed to the batteries of the nodes drain-out. Mobility makes the problem more complex, since the topology becomes more dynamic. Valera et al. [4] propose a routing protocol that caches packets and stores multiple routes to reduce the routing overhead associated with the route recovery procedure used to cope with broken links. Therefore, the proposed protocol aims to reduce the number of dropped packets and the energy consumed with routing activities. Yu and Lee [5] present two protocols based on the Dynamic Source Routing Protocol (DSR) [6] that aim to increase the network lifetime. The first protocol delays Route Requests on low-battery nodes whereas in and the second protocol a node waits for the arrival of multiple Route Requests to choose the better option.

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In this paper, we propose and analyze an energy-aware routing mechanism. Our energy-aware routing mechanism focuses on reactive protocols. In this work we implemented and analyzed the proposed mechanism over the Ad-Hoc On-Demand Distance Vector Routing (AODV) [7] protocol. The proposed mechanism modifies the route discovery procedure of AODV [7]. Our objective is to expand the network lifetime, or the time until the first node run out of energy, without additional complexity. To accomplish this, the proposed mechanism delays the forwarding of route requests according to the remaining energy on the nodes. To analyze the effects of this modification, we implemented a modified version of AODV in the Network Simulator (*ns*-2) [8]. Furthermore, we implemented a new energy model, more realistic, based on the analysis of Feeney and Nilsson [9].

This paper is organized as follows. In Section 2, we review the basic concepts of ad hoc routing. In Section 3, we describe the proposed energy-aware routing mechanism and discuss its implications. Section 4 details the simulations and analyzes the performance of the proposed mechanism. Finally, Section 5 summarizes the results and points out future research problems.

2 Routing in Ad Hoc Networks

The role of routing is to find, based on a specific metric, the most suitable route to forward data packets in a multi-hop network. In the case of ad hoc networks, every node is a potential router, because there is no infrastructure. Moreover, the autonomy of the ad hoc nodes prevents the formation of a hierarchical structure, making it difficult to the routing protocol to be scalable. Routing protocols like Routing Information Protocol (RIP) [10], based on distance-vectors, and Open Shortest Path First (OSPF) [11], link-state based, work correctly on wired networks that have a nearly static topology. Nevertheless, these protocols would have convergence problems in MANETs, which present dynamic topologies. Moreover, wireless transmission imposes some other difficulties to routing. One of these problems is the possibility of asymmetric links. When a signal is received on an asymmetric link, the routing protocol cannot extract any information about the reverse direction of that link. Another complication worth to mention is the varying connectivity of wireless networks. Each neighbor in the transmission range of a node is a possible route. Thus, the protocol is forced to deal with a great number of possible routes that changes over time according to the topology variations.

The ad hoc routing protocols can be divided in two large groups: the pro-active and the reactive, or on-demand, protocols. The pro-active protocols continuously evaluate routes by exchanging periodic control messages. Thus, when a data packet needs to be forwarded, the route is already known. In order to do that, the nodes maintain routing tables and perform updates as topological changes occur. Since the updates are periodical, there is a constant number of routing messages on the network, despite of the network load. The Destination-Sequenced Distance Vector (DSDV) [12] and the Optimized Link State Routing (OLSR) [13] are examples of proactive protocols. The reactive protocols, on the other hand, discover routes only when they are needed. Therefore, the route discovery procedure is trigged by the arrival of a data packet requiring forwarding. Reactive protocols do not exchange periodic messages, saving bandwidth and energy. The routing overhead of reactive protocols is depends on the network load and topology changes. Finally, the packet forwarding has a larger latency, due to the route discovery procedure. The two main studied reactive protocols are the Dynamic Source Routing (DSR) [6] and the Ad-hoc On-Demand Distance Vector Routing (AODV) [7].

This work focuses on reactive protocols, since these protocols aim at saving the network resources by discovering only part of the network topology. This limited knowledge makes it difficult to use energy-related metrics. The mechanism we propose later was implemented over the AODV protocol, which is currently under standardization process in the IETF.

The AODV protocol is a reactive protocol based on routing tables. This means that a node only needs to discover a route if there is no entry to the destination in its routing table. Despite of its on-demand nature, AODV needs to have local connectivity information to work properly. To obtain this knowledge, AODV may use two different mechanisms: a local broadcast of "Hello" messages or link-layer detection, that is, gathering the neighbor information from the MAC layer. In order to prevent the formation of loops, AODV uses sequence numbers.

When a route is needed, the source node broadcasts a route request (RREQ) packet containing, among other fields, the source address and an identifier, *broadcast_id*, which are used to uniquely identify one route discovery procedure. Each time a source starts a new route discovery process, the *broadcast_id* value is increased. The relay nodes receive the RREQ, increases the hop-count field and forward the packet. When a relay node forwards the RREQ to its neighbors, it stores the source and destination addresses, the *broadcast_id*, the reverse path lifetime, and the sequence number of the source, which may be used to answer to an eventual route request having the source node as destination. Each relay node processes only once any route discovery, dropping redundant RREQs. Eventually, the RREQ is received by the destination, or another relay node that has a valid routing table entry to the destination. A relay node may answer a RREQ if the sequence number of the destination contained at the routing table is newer than the sequence number of the route request. In order to answer a RREQ, a relay node with a valid routing entry to the destination, or the destination by itself, sends a route reply (RREP) packet in unicast to the source. The RREP contains the hop-count and the sequence number of the destination. As the RREP returns through the reverse path of the original RREQ, it establishes pointers to the destination. A relay node only forwards a redundant RREP if it contains a higher sequence number to the destination, or an equal sequence number with a lower hop-count, i.e. if it has a newer, or a shorter, route to the destination. The routing table has at most one entry to each destination, and each entry has a *route cache timeout*. If the *route cache timeout* expires, the entry is considered invalid. Additionally, each entry has a list of active neighbors that uses this route. The sequence numbers of the entries prevent the formation of loops.

3 The Proposed Energy-Aware Routing Mechanism

The idea of the proposed mechanism is to explore the discard of redundant route requests (RREQ) packets. The key idea is that each node that receives a RREQ message delays the forwarding procedure according to its remaining energy. Thus, RREQs forwarded by nodes with more energy, and therefore a lower delay, tend to be propagated first. Moreover, the RREQs forwarded by the nodes with less energy have a higher probability of being considered redundant, and of being consequently discarded. If the RREQ forwarded by a node with little remaining energy is discarded, this node will not be used as a route and will save energy. The process of discarding RREQs forwarded by nodes with less energy tend to balance the flows among different routes, since nodes with more energy have increased probability of being chosen as route. Thus, it avoids the use of the same route over and over. Therefore, the proposed energy-aware routing mechanism results in balanced remaining energy levels at the nodes, improving the network lifetime. The tradeoff of the proposed mechanism is that it increases the route discovery time.

The version of the AODV protocol with the above mechanism implemented, called Energy-Aware AODV (AODV-E), potentially provides a better energy consumption balance paying a higher route discovery delay.

3.1 The Delay Function

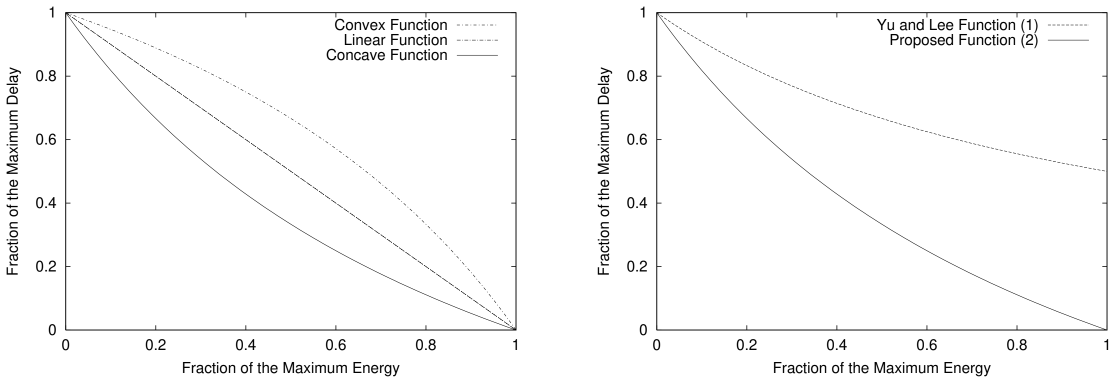
The forwarding delay of RREQ messages used in the routing mechanism is a function of the remaining energy of the node. Different functions can be used. Yu and Lee [5] analyzed three kinds of functions: convex, linear, and concave. These functions are presented in Figure 1(a). Although the linear and convex functions result in a higher delay for a given remaining energy level (Figure 1(a)), the concave function shows better results in extending the network lifetime. As a result of their analysis, Yu and Lee suggested the use of a simplified delay function. The suggested delay function has the form:

$$d_{i,t} = \frac{E \times D}{e_{i,t} + E} \quad , \tag{1}$$

where $d_{i,t}$ is the delay added to the forwarding by node i at time t, E is the initial energy of the node, D is the maximum delay allowed, and $e_{i,t}$ is the remaining energy of node i at time t.

The main problem with the delay function of Equation 1 is the minimum delay added, $\frac{D}{2}$. This means that even if a node is full of energy it will add an avoidable delay to the route discovery procedure. Moreover, the delay range is limited between $\frac{D}{2}$ and D. The difference of the delay added by a node with full energy and the delay added by a node near exhaustion is only $\frac{D}{2}$. In this paper, we propose the modification of the delay function of Equation 1 in order to reduce the delay included by a node with full energy to zero. The proposed function is:

$$d_{i,t} = \left(\frac{2D \times E}{e_{i,t} + E}\right) - D \quad , \tag{2}$$



(a) Delay functions behavior.

(b) Delay as a function of remaining energy.

Figure 1: Delay Functions.

where $d_{i,t}$ is the delay added to the forwarding by node i at time t, E is the initial energy of the node, D is the maximum delay allowed, and $e_{i,t}$ is the remaining energy of node i at time t.

The proposed delay function reduces the average forwarding delay and increases the difference of the delay added by a node with full energy and the delay added by a node near exhaustion. The reduced delay for nodes with more energy increases the probability that RREQs forwarded by nodes that are near exhaustion will be discarded. Additionally, a faster route discovery procedure is expected when the nodes have full energy. Figure 1(b) illustrates the difference between the two delay functions. From Figure 1(b) we can notice that as the nodes come closer to exhaustion, the added delay to the RREQs forwarding grows faster with the proposed function, reducing more aggressively the chance of one of these nodes being used as route. Based on this analysis, the proposed delay function was adopted in the proposed mechanism.

3.2 The Energy Consumption Model

There are basically two forms of transmitting a packet at the MAC layer: broadcast or unicast. When a packet is broadcasted, all the nodes in the transmission range receive it. Unicast packets, on the other hand, are received only by the node specified at the packet header, the other nodes in the transmission range only process the headers but discard the data. If we consider that the bandwidth, ideally, should be shared among all the nodes, most of the traffic received at the interface of the node is actually addressed to other nodes.

Feeney and Nilsson performed energy consumption measurements [9] with IEEE 802.11 [14] interfaces in ad hoc mode. In the experiments they used the *DSSS Lucent IEEE 802.11 WaveLAN PC "Bronze"* and *"Silver"* cards which operate at 2 Mbps and 11 Mbps, respectively. The results show that the power consumed in idle state and in ad hoc mode is 741 mW for the *"Silver"* card. The extra per packet energy consumption was modeled as a linear function of the packet length in bytes (excluding only MAC and PLCP headers) as follows:

$$E_c = m \times length + b \ , \tag{3}$$

where the parameters m and b are constants expressed in μJ for each one of the following cases: broadcast transmission, unicast transmission (using Request to Send/ Clear to Send handshake), broadcast receive, unicast receive (using RTS/CTS), overheard traffic from the unicast emitter, and overheard traffic from the unicast receiver. The consumption of an overhearing node is about four times lower than the consumption of the actual receiver. In Equation 3 it is clear that the energy consumption has a packet length dependent term and a fixed term. This suggests that the transmission of one large packet is more efficient than the transmission of the same information using small packets.

The proposed mechanism was analyzed using the *Network Simulator* - *ns*-2 [8]. The energy model implemented by *ns*-2 does not take into account, in the unicast packet reception, if the node is the receiver or an overhearing node. This abstraction has a larger impact when the node density is high because there are more overhearing nodes.

To have more realistic results, we implemented a new energy model inside the *ns*-2, based on the results of Feeney and Nilsson [9] for the 11 Mbps card. The parameters used in our energy model are in Table 1. The last two rows of Table 1 refer to the consumption of an overhearing node.

Table 1: Values used in the implemented model.

Energy Consumption Event	m (μ**J**)	b (μ**J**)
Point-to-point transmission	0,48	431
Broadcast transmission	2,1	272
Point-to-point reception	0,12	316
Broadcast reception	0,26	50
Overheard traffic originated by the emitter	0,11	42
Overheard traffic originated by the receiver	0	38

Since the presented measurements do not take into account the energy consumed in unsuccessful attempts to acquire the channel (contention), this model is inadequate to highly loaded networks, where this event occurs frequently. Moreover, the implementation assumes that a node overhearing a packet overhears the associated RTS too, and that a node overhearing a CTS packet will overhear the ACK. Hence, the implemented model is realistic for low load and low mobility scenarios, where these hypotheses hold.

4 Performance Analysis of AODV-E

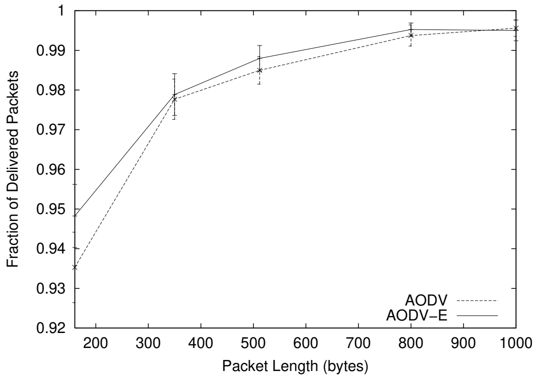
In order to analyze the efficiency of the proposed mechanism, the results of the Energy-Aware AODV (AODV-E) were compared with the results of the original AODV using the same scenarios. The main goal of these simulations is to evaluate the energy consumption balance of AODV-E and the implications of this in the network lifetime. Besides that, to analyze the effects of the fixed term of the packet energy consumption, the simulations were repeated with different packets lengths (160, 350, 512, 800, and 1000 bytes) without variation of the source rates. All the simulations were performed with 60 nodes equipped with IEEE 802.11 interfaces operating at 11 Mbps and with initial energy of 5J. To simplify the model, the power consumption of the idle state was set to 0 W. The maximum delay introduced in the RREQ forwarding was 100 ms. All the nodes move with an average speed of 1 m/s, uniformly distributed between 0,9 and 1,1 m/s, in a 1200 m x 600 m area. In each simulation run, there are two simultaneous sources emitting at 64 kbps. These simulations were performed using version 2.1b9a of *ns*-2 [8].

We defined two different groups of simulations, one to evaluate the energy consumption balance among the nodes and the other to analyze the improvement in the network lifetime, defined as the time until the first node runs out of energy. All the results are presented with a 95% confidence interval to the mean value. These intervals are represented as vertical bars in the graphs.

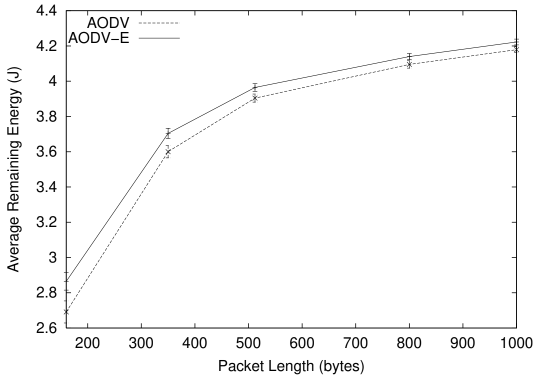
4.1 Energy Balance Analysis

To analyze the energy consumption balance, we performed 100 seconds simulations with all nodes being either source, or destination, for 6 seconds. Thus, at the end of the simulation we can divide the nodes into two groups: the sources and the destinations of connections. Therefore, if all the nodes had the same routing tasks, the nodes in each of the two groups would have the same energy. This would lead to an optimum energy balance. The simulation time was chosen in order to guarantee that no node would run out of energy during the simulation. Each node transmits, for each packet length, the same number of packets during each simulation. The used metrics were the fraction of delivered packets, which evaluates the influence of the proposed mechanism. The second metric is the average remaining energy of the nodes. This metric expresses the total amount of energy spent. Additionally, the variance of the remaining energy of the nodes measures the energy consumption balance achieved.

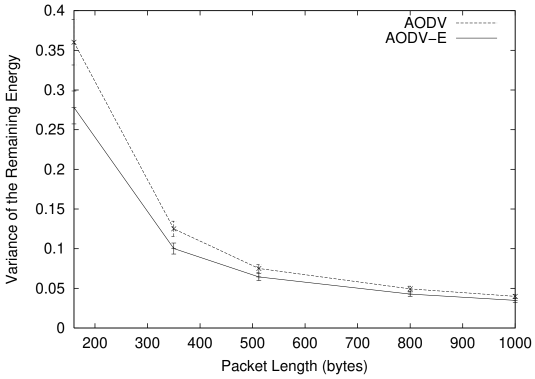
Figure 2(a) shows the fraction of delivered packets achieved by the two protocols. Both of them present a high delivery rate, near 100%, because the scenario has the low mobility and low load. AODV and AODV-E are



(a) Fraction of packets delivered by the protocols.



(b) Average remaining energy of the nodes.



(c) Variance of the remaining energy of the nodes.

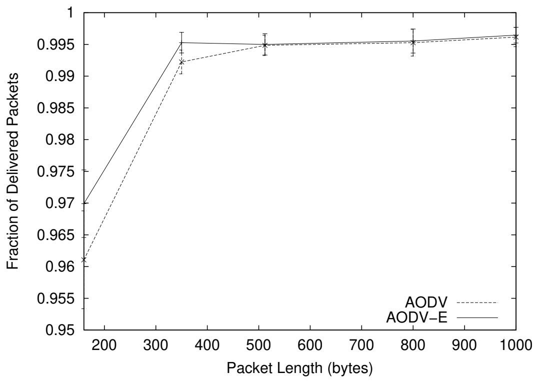
Figure 2: Energy balance results.

equivalent for this metric. Figure 2(b) shows the average remaining energy of the nodes after the end of simulation. The results demonstrate the low energy efficiency of small packets. When using small packets, the fixed term of the energy cost is more significant. As the packet length increases, the difference of energy consumption for consecutive packet lengths gets proportionally lower. The average remaining energy of the nodes when using AODV-E is slightly higher, which indicates that, considering the total energy consumption, AODV-E is more efficient. Finally, Figure 2(c) presents the variance of the remaining energy of the nodes. AODV-E results in a variance reduction of 20% for small packets and of 12% for 1000 bytes packets. These results evidence the energy consumption balance of the proposed mechanism.

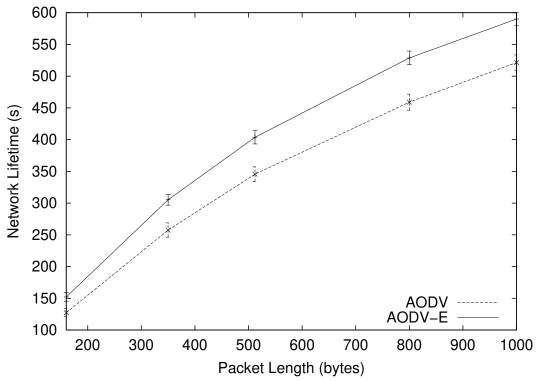
4.2 Network Lifetime Analysis

In order to analyze the network lifetime, more generic traffic patterns were used. The sources rates were fixed, but the duration of the connections was uniformly distributed between 5 and 15 seconds. These connections are independently established between two nodes picked at random. In these simulations, besides packet delivery fraction we measured the network lifetime (time until the first node runs out of energy) that gives the period during which the network is fully operational. We also measured the number of received packets, which shows the effect of the fixed term of the energy consumption, and the total amount of data received, which demonstrates how many data bits were actually delivered by each protocol during the network lifetime.

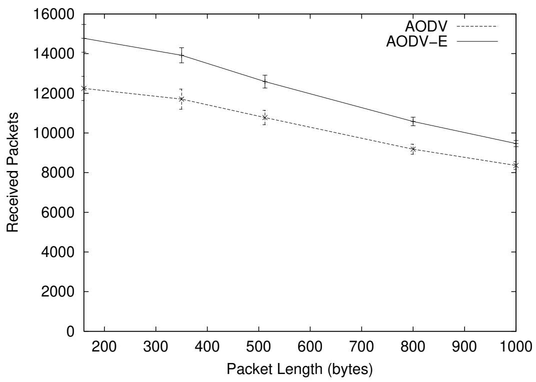
Figure 3(a) confirms the equivalent performance of the two protocols and the high delivery rate achieved. As



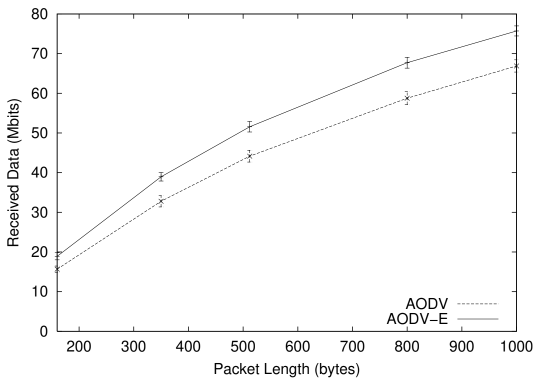
(a) Fraction of delivered packets during the network lifetime.



(b) Network lifetime with the two protocols.



(c) Received packets during network lifetime.



(d) Total of bits received during network lifetime.

Figure 3: Network lifetime results.

we can see in Figure 3(b), the mechanism proposed in AODV-E improves the network lifetime. This improvement is more significant for small packets, when the reduction of the variance of the remaining energy (showed in Figure 2(c)) is higher. The proposed mechanism increases the network lifetime from 19%, for 160 bytes packets, to 13%, for 1000 bytes packets. Figure 3(c) shows that the number of received packets increases proportionally to the network lifetime. Nevertheless, if we observe each curve individually, we can conclude that the number of packets received does not decrease at the same rate as the increase rate in packet length. This is explained by the high fixed cost of packet transmission. Finally, Figure 3(d) presents the total amount of data successfully received. Naturally, the curves show the same behavior of the network lifetime because, roughly, each second represents 128 kbits. This figure evidences that the use of small packets results in the transmission of much less bits. Considering the initial energy of 5 J, the absolute gain with AODV-E ranged from 3 Mbits (20%), for small packets, to 8 Mbits (13%), for large packets.

5 Conclusions

This paper proposed an energy-aware routing mechanism for mobile ad hoc networks. In order to analyze the performance of this mechanism, we implemented a realistic energy model in the network simulator *ns*-2. The implemented model takes into account the way the packet is transmitted and the role of each node in the communication. The energy-aware routing mechanism was implemented and introduced into the AODV routing protocol.

The resulting protocol was called AODV-E.

We demonstrated through variations on the packet length that the use of small packets is inefficient in terms of the energy consumption. This is due to the fixed cost of each packet transmission. When using small packets the fixed cost can even overcome the variable cost that depends on the packet length. Therefore, as the packet length increases, the difference of the consumption between consecutive packet lengths becomes less significant.

The proposed mechanism, implemented on AODV-E, improves the energy consumption balance among the nodes. The results show that the variance of the remaining energy is reduced between 20%, for small packets, and 12%, for large packets, compared with the original AODV. The better energy consumption balance increases the network lifetime. The network lifetime increases from 19% for small packets to 13% for large packets, as well as the total amount of data transmitted during network lifetime.

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