Energy-awareness Metrics for Multihop Wireless User-centric Routing

Antonio Junior[1], **Rute Sofia**[1], **and Antonio Costa**[2]
[1]SITI, University Lusofona, Lisbon, Portugal
[2]ALGORITMI, University of Minho, Braga, Portugal

Abstract— *This paper proposes and validates energy-awareness node-based ranking and energy-awareness successor-based ranking routing metrics focused on improving energy efficiency of multihop approaches in heterogeneous wireless environments. The validation is carried out through discrete event simulations based on real data set traces and controlled random topologies for the specific case of AODV.*

Keywords: Multihop routing; energy-efficiency; wireless user-centric networks.

1. Introduction

The recent advances in wireless technologies a such as *Wireless Fidelity (Wi-Fi)* is assisting the rise of *User-Centric Networking (UCNs)* architectures, i.e., architectures where nodes are often carried by regular Internet end-users [1], [2]. Examples of such environments can be a network formed on-the-fly after a disaster of some nature or even a municipality network where some nodes are based on end-user devices (through Internet access sharing).

Albeit being often spontaneously deployed, user-centric wireless environments rely on traditional multihop routing approaches. Multihop routing has been extensively analyzed and optimized in terms of resource management, but in terms of energy-efficiency, there is a lack of a thorough analysis. In other words, multihop routing is shortest-path based, but the metrics applied today normally relate to *Quality of Service (QoS)* aspects, or to hop count. In terms of energy-awareness, these protocols are lagging behind.

We highlight that there is considerable related work in the fields of energy-efficiency and energy-awareness for sensor networks. However, these are environments where nodes are homogeneous in terms of energy capability, and the architectures are often static. In contrast, in user-centric networks, nodes are expected to be heterogeneous in terms of energy resources, and the topology exhibits high variability as nodes tend to disappear and appear in the network, based on their carriers interests and behavior.

In previous work [3], [4] we have discussed the potential of current energy-aware routing approaches for wireless networks, and whether or not they may make sense when applied to routing in user-centric environments. We have also proposed concepts that could assist in making multihop routing more efficient in terms of energy-awareness that consider heterogeneous devices, without necessarily having to change operational aspects of the underlying algorithms, or protocols. Following such line of thought, this paper proposes and validates two routing metrics to improve network lifetime based on current multihop approaches. The first metric is based on a single (source node) energy-awareness perspective, while the second is based on the perspective introduced by the source node and potential successors. What we want to analyze is up to which point can a combination of the perspective of both a source and successor node improve network lifetime.

We evaluate the proposed metrics through discrete event simulations based on realistic assumptions based on the *Ad-Hoc On-demand Distance Vector Protocol (AODV)* [5], being the goal to analyze whether or not this approach can improve the overall network lifetime, without incurring a significant penalty.

The rest of this paper is organized as follows. Section 2 describes related work focused on multihop energy-efficiency. Section 3 goes over the discussion on energy awareness with single node vs. the two node association perspective in multihop routing. Section 4 describes our proposed metrics. In section 5, we present the performance evaluation while section 6 presents the evaluation results. Conclusions and future work are presented in section 7.

2. Related Work

A few approaches [6], [7] have surveyed multihop proposals focused on energy-efficiency, considering both the energy spent when nodes are engaged in active communication or passive communication, i.e., in idle mode. Such work has as underlying scenarios homogeneous environments, and several proposals combine different energy-aware metrics to maximize the network lifetime.

Relevant proposals [8], [9], [10] making multihop routing adaptive, have explored new metrics having in mind different types of optimization, e.g., reduction of energy spent across a path, considering the residual energy capacity of a node or avoiding nodes with low residual energy, on the global network.

Another relevant overview [11] has been provided by C. K. Toh, who discusses different routing properties to consider in multihop routing. One of them is efficient utilization of battery capacity. In this work, the author also addresses the performance of power efficiency in ad-hoc mobile networks by analyzing four approaches which have as common goal to select an optimal path, being the optimum the minimization of the total power required on the network (across all nodes) and also the maximization of the lifetime of all nodes in the network.

The *Energy-efficient Unified Routing (EURo)* [12] develop an routing scheme that accommodates any combination of transmission power, interference and residual energy to optimize the energy efficiency of multihop wireless networks. The E^2R routing protocol [13] uses an opportunistic forwarding scheme to deliver control messages and data packets in a multihop wireless network to energy efficiency in multihop green wireless networks. Unlike other opportunistic routing protocols, it neither uses pre-selected static paths nor does it prepare forwarding candidates.

The authors of [14] outline some steps towards the definition of energy efficiency metrics for designing energy-aware wireless network. The approach is to estimate the optimal message size in terms of power consumption, to estimate the average amount of energy spent to transmit one bit and the relationship between traffic and power consumption. However, an energy-aware metric for multihop routing is not defined.

The *Maximum Residual Packet Capacity (MRPC)* protocol [15] comprises a node perspective parameter (battery power of the node) and a link perspective parameter (packet transmission energy in a link) across the link between nodes. MRPC identifies the capacity of a node not just by its residual battery energy, but also by the expected energy spent in reliably forwarding a packet over a specific link. However, such formulation is more adequate to capture scenarios where the link transmission cost depends on the physical distance between nodes and on the link error rates. Hence, the approach does not consider a energy-awareness as a primary resource of the network.

Zhang et. al. [16] combine node lifetime and link lifetime between every two adjacent nodes to select an optimal path. This route lifetime prediction algorithm explores the dynamic nature of mobile nodes in a route discovery period for predicting the lifetime of routes discovered, and then select the longest lifetime route for persistent data forwarding when making a route decision. The dynamic nature of mobile nodes mentioned, make use of the energy drain rate of nodes and the relative mobility estimation rate of adjacent nodes. However, this work does not consider the energy-awareness as a prime metric for the wireless link between two nodes, i.e. successor-based metric. Our work is in line with this, as we also attempt to explore combinations between a source and a successor node, to increase the network lifetime.

Finally, we highlight that *The Internet Engineering Task Force (IETF)* Working Group *Routing Over Low Power and Lossy Networks (ROLL)* is currently discussing multihop metrics tailored to energy-efficiency [17].

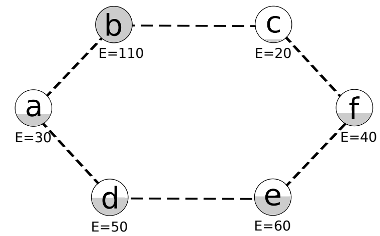

Fig. 1: Approaches of energy-aware metrics.

3. Energy Awareness in Multihop Routing, Single Node vs. the Two Node Association Perspective

In previous work [3], [4], we have considered energy-awareness based on a single node perspective. In other words, when building a shortest-path we take into consideration a node "energy-aware" cost.

During our research, we have realized that despite such approach providing a significant improvement, there are cases that could benefit, at a first glance, of a cost derived of the energy-awareness of two nodes, the father and the successor on different paths, in particular considering multihop on-demand approaches, where the information (node cost) will be provided from source to destination, but the path itself will only be available based on responses from the nodes involved. One of such cases is illustrated in Figure 1, where we consider two possible paths between source node a and destination f. A example of the energy-awareness cost provided by our metric is represented by E. As there are two potential paths, let us assume that based on shortest-path computation and on our metric, the best path would be the one providing a global higher level of E (the higher sum). Hence, the path $a-b-c-f$ (total cost of 200 units) would be preferred over path $a-d-e-f$ (total cost of 180). However, looking at the global topology we can see that path $a-b-c-f$ has an energy bottleneck (node c) and depending on traffic flowing, choosing this path may result in nodes having to recompute the path between a and f. If node b (as father node) had a perception that its neighbor node c (as successor node) would soon no longer be available, it could announce a lower value for its weight. Node c would do the same, and hence there seems to be some probability for path $a-d-e-f$ to be chosen over $a-b-c-f$. This is a simple example that considering the energy cost derived of the energy-awareness of an association between two nodes is advantageous, since it may give a perspective on the duration of a link between the nodes, based on the nodes energy capacity and drain rates.

The situations mentioned, of fluctuations in terms of energy-awareness concerning path computation in multipath environments are expected to be more serious in UCNs, as this networks are expected to exhibit more variability in terms of node movement. User-centric routing has therefore to take into consideration some aspects which are intrinsic to the way that humans move and establish social contacts. Thus, the relation between a father and a successor node seems to be relevant to be considered also from an energy-awareness perspective. We highlight that there is a different between energy-awareness from a link perspective and energy-awareness derived from the association of two specific nodes. The former relates to the link quality itself; while the latter is simply a composition of the energy-awareness level of two associated nodes.

Hence, we address in the next section our proposed heuristics, which are based on the association of father and successor node.

4. Our Proposal

This section provides an overview on our heuristics. In previous work we have proposed and validated an energy-awareness metric which we named as *Enery-awareness Node Ranking (ENR)* [18][1]. In this section, we build on top of this node-based cost, but consider a father/successor approach.

Based on the notion that in UCNs nodes are heterogeneous in terms of energy capacity ENR explores the fact that nodes that have been in idle mode for the majority of their lifetime, and that still exhibit a good estimate for their future energy level are the most adequate candidates to constitute a shortest-path.

In ENR we estimate how much of its lifetime has node i been in idle mode, to then provide an estimate towards the node's future energy expenditure, as this will for sure impact the node's lifetime. Such periods are the ones that are expensive to i in terms of energy. Hence, we consider the total period in idle time, t_{idle} over the full lifetime expected for a specific node, which is given by the sum of the elapsed time period T with the estimated lifetime of the node, as provided in equation 1. The estimated lifetime $C(i)$ provided by Garcia-Luna-Aceves et. al. [19] have considered the ratio between residual energy and drain rate which can capture the heterogeneous energy capability of nodes.

$$ENR(i) = \frac{T - t_{idle}}{T \times C(i)} \quad (1)$$

ENR is therefore a node weight which provides a ranking in terms of the node robustness, from an energy perspective, and having as goal to optimize the network lifetime. The smaller $ENR(i)$ is, the more likelihood a node has to be part of a path.

Based on ENR, we consider in this work the *Energy-awareness Father-Son (EFS)* metric, which considers a composition of the ENRs of both a father and successor nodes (c.f. Figure 2), as specified in equation 2.

[1] Short version under submission.

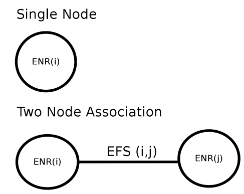

Fig. 2: Perspectives of the metrics.

$$EFS(i,j) = ENR(i) \times ENR(j) \quad (2)$$

EFS provides a ranking which we believe is useful to assist the routing algorithm to converge quickly in particular in multipath environments, as the selection on which successor to consider shall be made up from, by the father node. The goal is, similarly to ENR, to improve the network lifetime without disrupting the overall network operation. Hence, the smaller $EFS(i,j)$ is, the more likelihood a link has to become part of a path.

5. Performance Evaluation

This section provides a performance evaluation for EFS having as benchmark native AODV, as well as our previously proposed metric ENR. The evaluation has been performed by carrying out NS-2 (version 2.34) simulations. The scenarios are *Wireless Fidelity (Wi-Fi)* based. We have considered the NS-2 default physical layer, two-ray ground propagation model and DCF *(Distributed Coordination Function*) for MAC layer with 802.11g parameters.

For AODV we considered the native NS-2 module, here referenced as *AODV-native.* This module, *AODV-native,* considers hop-count as the metric to compute a shortest-path. Moreover, the original $C(i)$ has been developed to be applied to *Dynamic Source Routing (DSR)* protocol. The original specification of $C(i)$ therefore selects a best path based on a *min-max* approach, where the best path is the one that has the lowest bottleneck in terms of energy. Hence, we adapted the AODV to select the path in a min-max way as the original specification of the $C(i)$. We refer to this implementation as *AODV-minmax*. *AODV-ENR* and *AODV-EFS* represent AODV with our two metrics ENR and EFS, respectively. We describe next the topologies that have been considered in this evaluation.

5.1 Scenario 1 - Small Topologies

For this first scenario we have considered 25 nodes randomly distributed across a square with an area of 400m x 400m and 800m x 800m, respectively. We then considered a Poisson traffic model where each flow is based on *Variable Bit Rate (VBR)*, average packet size of 512 bytes, sending rate of 256 Kbps. Sources and destinations are randomly selected from the available nodes. Then, we consider 2 and 4 flows as a way to represent two different load levels. The

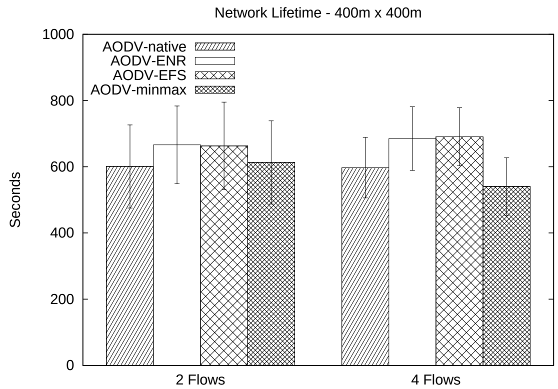

Fig. 3: Scenario-1, 400m x 400m.

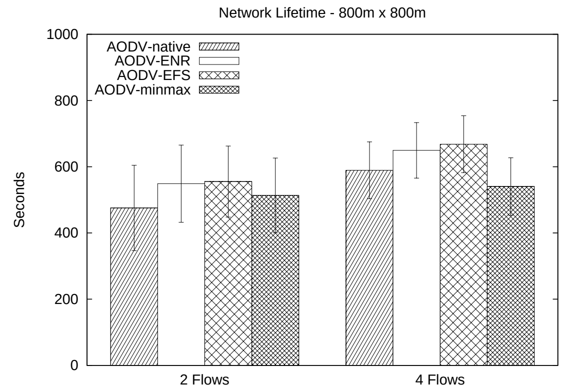

Fig. 4: Scenario-1, 800m x 800m.

simulation time has been set to 1000 seconds. In these set of experiments, all of the nodes are static, as what is relevant to us is to understand how the network behaves in terms of energy consumption. Hence, each node has been modeled to have different levels of energy parameters in order to represent heterogeneous Wi-Fi enable devices.

5.2 Scenario 2 - Traces-based Topology

For the design of this case, we have considered the settings that were obtained on traces available in the CRAWDAD project (*A Community Resource for Archiving Wireless Data At Dartmouth*) to be an example of a real environment to evaluate our proposed energy-awareness ranking metrics.

These traces have been collected based on GPS receivers, which logged data every 10 seconds. The NCSU scenario [20] comprises a human mobility data collected from 35 trace files, each corresponding to the perspective of a single node in one day, i.e., 24 hours. NCSU relies on a topology area of 2586.85 meters (X length) by 2347 meters (Y length) considering an uniform node speed of one meter per second (m/s). The authors have randomly selected 20 participants out of the students sharing a common interest, i.e., enrolled on the computer science department. Hence, more than one node contributed to different trace files, which there is no way to distinguish and to understand which node provided which trace.

For fair as possible, we have considered the same previews Poisson traffic model.

6. Evaluation Results

The results extracted intend to analyze benefits in terms of *network lifetime*. We define network lifetime as the time period since a topology becomes active, until a topology becomes disconnected, from the perspective of destination nodes. In other words, such time period is counted since the topology becomes active, until a destination cannot be reached by any of the available sources in the topology.

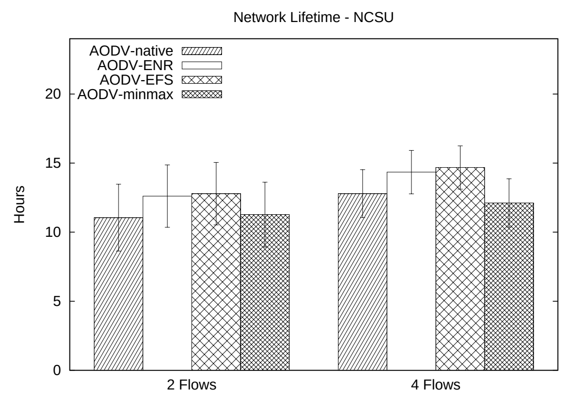

Fig. 5: Scenario-2.

Even though we analyze benefits in terms of network lifetime, we also want to understand the impact of the metrics in the overall network performance. For that, we consider three additional aspects: (i) *average end-to-end delay*, the time a packet takes between source and destination, comprising propagation and queuing delay. The end-to-end delay is computed per destination and then averaged across all destinations; (ii) *throughput*, the average number of bytes reaching destination nodes, measured in Kbps. The results presented correspond to the average throughput in the network, which is computed first per destination and then averaged across all destinations in the network; (iii) *average packet loss*, the percentage of packets that does not reach the destination. Average packet loss corresponds to the number of packets dropped between source and destination, averaged across all of the destinations.

To generate statistical sound results we relied on Akaroa2 [21]. All results have been computed within a 95% confidence interval.

6.1 Network Lifetime

To better analyze if our metrics behave coherently across different scenarios, based on the parameters described, all

Table 1: Network lifetime improvement.

AODV	400m x 400m		800m x 800m		NCSU	
	2flows	4flows	2flows	4flows	2flows	4flows
ENR	10.9%	14.7%	15.4%	10.2%	14.2%	12.1%
EFS	10.3%	15.6%	16.7%	13.4%	15.8%	14.7%
minmax	2.0%	-9.5%	7.9%	-8.3%	2.0%	-5.2%

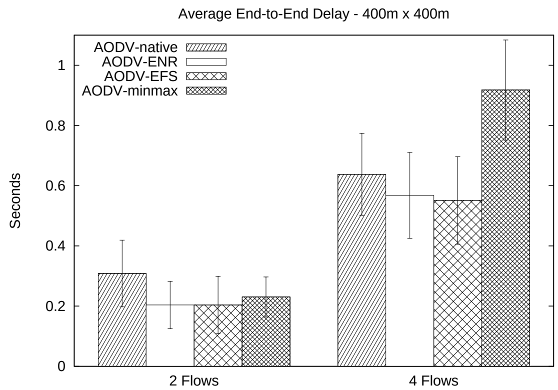

Fig. 6: Scenario-1, 400m x 400m.

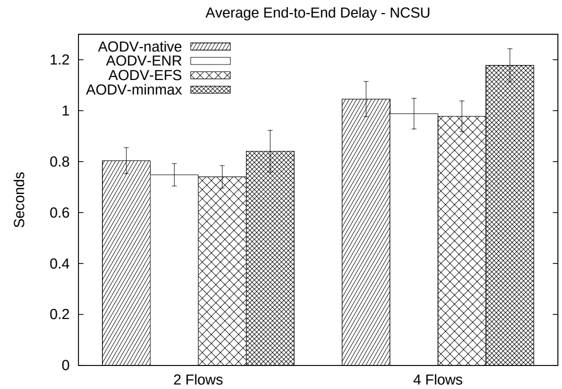

Fig. 8: Scenario-2.

Table 2: End-to-end delay improvement.

AODV	400m x 400m		800m x 800m		NCSU	
	2flows	4flows	2flows	4flows	2flows	4flows
ENR	33.9%	10.9%	2.6%	14.8%	6.9%	5.5%
EFS	34.0%	13.6%	6.4%	20.3%	7.9%	6.5%
minmax	25.2%	-44%	-3.6%	-3.3%	-4.6%	-12.6%

of the nodes of the described topologies have been set with initial energy levels picked up randomly. During the simulation we have observed that circa of 30% of nodes go down. Figures 3, 4 and 5 shows the average network lifetime for the different approaches. The X-axis represents the number of flows, while the Y-axis provides the network lifetime in seconds for Scenario-1 (cf. Figures 3 and 4) and in hours for Scenario-2 (cf. Figure 5).

Globally, as shown both metrics exhibit better results. In terms of EFS, we can see that in Scenario-1 there is no improvement when compared to ENR. We believe this occurs due to the fact that this is a very dense network and nodes travel short distances with a slow speed - the paths are quickly established and even though the nodes energy-levels are heterogeneous.

When the area changes (refer to Figure 4) then some improvement becomes visible, in particular for more congested networks. The same behavior occurs for Scenario-2, which points out that with realistic settings the improvement are similar.

While our metrics do stable behavior, the *AODV-minmax* varies according to the topology. For this concrete simulation scenarios, Table 1 provides the same results in percentage which show that the improvement provided by EFS becomes higher for multipath environments and when the network is more congested.

6.2 End-to-end Delay

As our main goal is to extend network lifetime without penalizing the end-to-end delay, throughput and packet loss,

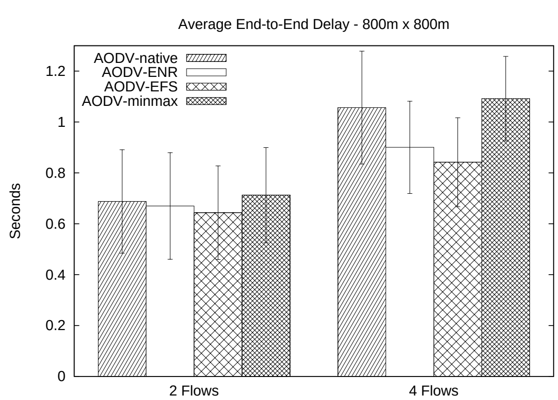

Fig. 7: Scenario-1, 800m x 800m.

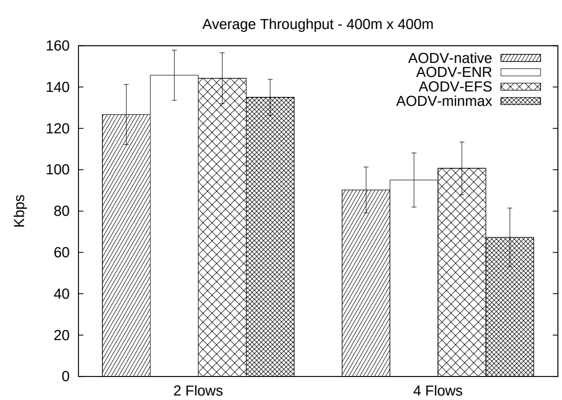

Fig. 9: Scenario-1, 400m x 400m.

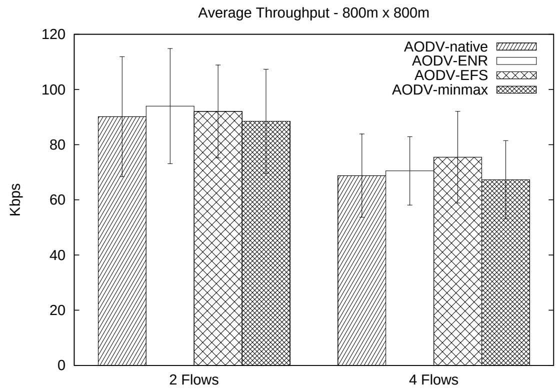

Fig. 10: Scenario-1, 800m x 800m.

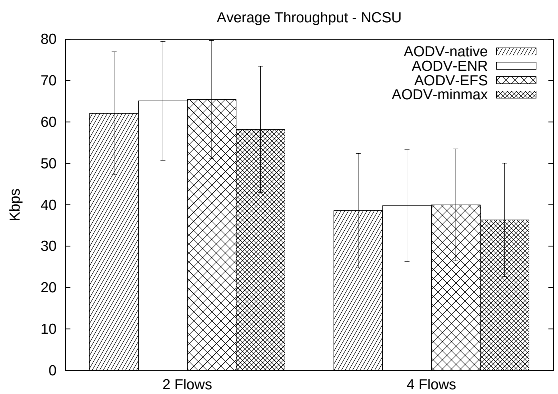

Fig. 11: Scenario-2.

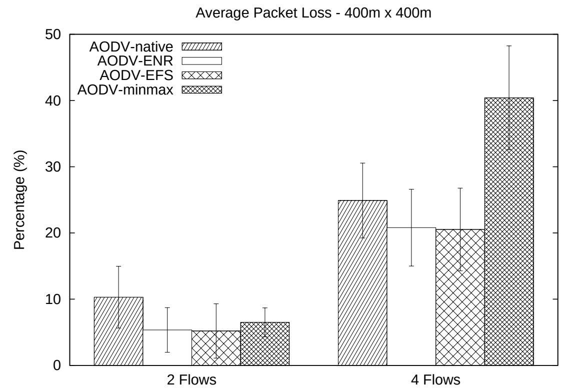

Fig. 12: Scenario-1, 400m x 400m.

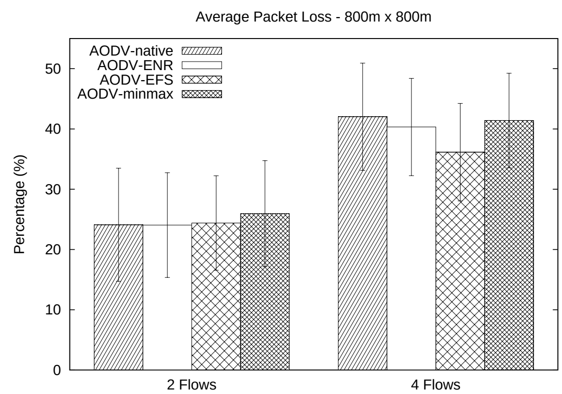

Fig. 13: Scenario-1, 800m x 800m.

Figures 6, 7 and 8 shows the average end-to-end delay achieved by applying EFS in comparison to the other approaches. We now consider only Scenario-2. The improvement margin against native AODV is provided in Table 2.

As shown both our metrics generate significantly less end-to-end delay. Across scenarios with higher load traffic, the *AODV-EFS* provides a higher gain. The reason for EFS to provide a higher gain in terms of delay reduction relates to the nodes selecting quicker a hop on the path by considering an association between two node as binding cost metric.

6.3 Throughput

We have then analyzed throughput impact and Figures 9, 10 and 11 shows the average throughput for the scenarios that have been set.

Table 3 provides the throughput gain against AODV. There is a slight gain of *AODV-ENR* and *AODV-EFS* in comparison to *AODV-native*. The gain provided by EFS is comparable to the gain provided by ENR for less congested networks. When the load on the network increases, then EFS provides slightly better values.

6.4 Packet Loss

We have analyzed the packet loss impact and Figures 12, 13 and 14 shows results obtained for all approaches, while Table 4 provides the gain derived from applying each metric, against native AODV.

For packet loss, EFS provides a higher gain across all scenarios, but becoming significantly higher for scenarios where nodes seem to be more mobile (larger distances) and the network is more congested.

Table 3: Throughput *gain*.

AODV	400m x 400m		800m x 800m		NCSU	
	2flows	4flows	2flows	4flows	2flows	4flows
ENR	15%	5.3%	4.2%	2.5%	4.8%	3.2%
EFS	13.9%	11.6%	2.1%	9.7%	5.3%	3.7%
minmax	6.5%	-25.4%	-1.9%	-2.2%	-6.3%	-5.8%

Table 4: Packet loss *gain*.

AODV	400m x 400m		800m x 800m		NCSU	
	2flows	4flows	2flows	4flows	2flows	4flows
ENR	48.0%	16.4%	0.2%	4.0%	4.1%	2.0%
EFS	49.5%	17.6%	1.3%	14.0%	5.0%	2.8%
minmax	36.8%	-62.2%	-7.7%	-1.5%	-5.2%	-4.3%

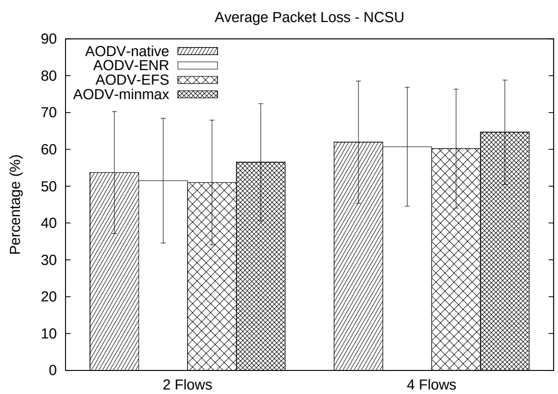

Fig. 14: Scenario-2.

7. Conclusions

In this paper we discuss and propose energy-awareness routing metrics that can provide stability in terms of network lifetime to multihop shortest-path based routing, without incurring strong penalties in terms of operational changes and maintenance. We have evaluated the our proposed metrics based on realistic settings for a specific case of on-demand routing, AODV.

We have shown that the energy-awareness metrics being proposed significantly improve AODV behavior in terms of network lifetime and also in terms of overall network operation, based upon throughput, packet loss, end-to-end delay.

In terms of the behavior of EFS vs. ENR there seems to be an improvement in particular when scenarios have larger distances, and when the network load is higher. This implies that EFS seems to provide more robustness when scenarios have more variability (e.g. more nodes moving, and several successors at disposal). In terms of network lifetime and for the scenarios evaluated, EFS results in a small improvement. We intend to explore further scenarios to analyze whether or not these conditions always hold. The end-to-end delay is also slightly improved.

The greater advantage of applying EFS instead of ENR seems to relate with an improvement in throughput and a significant improvement concerning packet loss. Our belief for this gain relates to the fact that EFS allows nodes to react quicker to energy changes on a path - resulting paths will be more robust earlier in time, assuming that nodes have a reasonable out-degree (several successors available).

We are currently carrying on this work both by fine-tuning not only scenarios but also the proposed metrics by evaluating their potential contribution for other forms of multihop routing, e.g. link state routing by *Optimized Link State Routing (OLSR)* protocol. As future work, we also intend to release the metrics explaining how they can be applied to the two main families of shortest-path routing, i.e., link state and distance-vector approaches.

Acknowledgment

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