An Evaluation Study of a Fair Energy-Efficient Technique for Mobile Ad Hoc Networks

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Abstract—In this study, we present a performance evaluation of an energy conservation technique designed for mobile ad hoc networks. This technique was designed with energy fairness central to its operation. This algorithm is not a routing algorithm. It works with existing routing protocols to complement their functionality from an energy-efficiency perspective. We show that this technique scales well with increased network traffic and population. We also compare it to the on-demand power management algorithm, a technique specifically designed to reduce idle energy consumption. Our comparison shows that our technique performs better in terms of energy savings and fairness as well as network lifetime extension.

Index Terms—Energy-efficient algorithms, mobile ad hoc networks, routing and forwarding, wireless networks.

I. INTRODUCTION

NOWADAYS, mobile ad hoc networks (MANET) are used in many applications [11]. Examples of these applications are conferences with attendees on the move with portable devices, sensor networks, wireless mesh networks, military operations and search and rescue operations. Multi-hop wireless networking of battery-operated devices is also a basic infrastructure of pervasive applications and architectures. Every day, new mobile communication devices are invented or enhanced with new capabilities, which adds new dimensions to the possible uses of ad hoc networks.

Nodes within a mobile ad hoc network communicate via wireless interfaces. This introduces some issues to their operation. One of the most important issues is the limited energy, which is usually supplied by node batteries, that network nodes possess. Amongst other sources, energy is consumed by wireless interfaces in several modes of operation [6],[13]. While communicating, nodes expend energy in packet sending and receiving modes. It has been shown that nodes also consume energy through their wireless interfaces while idle [13]. Idle energy consumption has been shown to be significant and often represents more than 50% of the overall energy consumption of the wireless interfaces. This source of energy consumption is unwanted and should therefore be eliminated or reduced by utilizing an energy conservation strategy. In order to address this type of energy consumption, the wireless interfaces of network nodes need to be put to sleep for periods of time, especially when they are not being used to exchange useful traffic. This can introduce many challenges to a scheme that handles this operation. For example, when should a node be put to sleep without knowing in advance the profile of the traffic that it will be required to handle? When does a sleeping node wake up? How would a node know that its neighbor with which it needs to communicate is asleep and when will it wake up? These questions and others need to be addressed by the energy conservation scheme.

Several schemes have been developed for the purpose of achieving energy-efficiency. Some of these schemes focused on creating energy-efficient routing strategies, while others focused on reducing idle energy consumption. These different schemes used various strategies to address energy conservation issues. For example, some of the schemes are cluster-based e.g. [2],[14] while others are distributed e.g. [8],[16]. From another point of view, some of the schemes that depend on putting nodes to sleep are asynchronous e.g. [8],[15],[16] while others are synchronous e.g. [17]. In most schemes, however, energy fairness between network nodes was not directly addressed. It has been shown [1] that fairness in energy consumption between network nodes has a significant effect on extending network lifetime.

In this study, we evaluate the performance of an energy-efficient scheme [8] that is designed to address many of the issues mentioned above. It was designed with energy fairness central to its operation. It works with existing ad hoc routing protocols to complement their functionality from an energy-efficiency perspective. In [8], we showed that this technique performs well with the different categories of ad hoc routing protocols. In this study, we show that it scales well with increased network population and traffic. Finally we compare its performance with that of the on-demand power management scheme [16]. Through this comparison, we show the significant network lifetime and data delivery performance enhancement that our techniques has over the routing protocol alone and over another power saving algorithm of the same category.

This paper is organized as follows. In Section II, we present some of the related studies. In Section III, we briefly review the technique under evaluation. In Section IV, we present the results of our evaluation experiments. In Section V, we conclude the study and give some suggestions for future work.
II. RELATED WORK

In IEEE 802.11 power management [17], the node’s transceiver is switched off whenever it is not needed. Since there is no way to predict in advance when the transceiver should expect to receive packets, it has to wake up periodically. Data get buffered in the senders when the receivers are in the sleep state. In ad hoc mode, all nodes in the network are synchronized to wake up at the beginning of each beacon period. Messages are sent during the period when all nodes are awake. Data transmission is done by signaling the existence of data that needs sending and specifying the receivers of this data inside a small interval called ATIM at the beginning of each beacon interval. If any node receives a message indicating that there is data for it, it acknowledges and stays awake for the rest of the beacon interval. All other nodes can go to sleep after the ATIM window is over. Nodes that have buffered data can then transmit this data during the rest of the beacon interval. This power management scheme has some drawbacks. For example, it requires a complete synchronization of all network nodes to wake up at exactly the same time. It can lead to severe collisions in case of heavy traffic networks especially during the ATIM window. This could lead to severe delays and reduced throughput. This calls into question the scalability of this power management scheme.

In SPAN [2], routing duties are performed by “coordinator” nodes. A node’s decision to become a coordinator is based on the amount of remaining energy it possesses and the number of pairs of neighbors it can connect together. Therefore, coordinators stay awake continuously and perform multi-hop packet routing within the network while other nodes remain in energy saving mode and periodically check to see if they should wake up and become coordinators. SPAN requires modifications to the route lookup process at each node. At any time only those entries in a node’s routing table that correspond to currently active coordinators can be used as valid next hops. The energy balance that SPAN can perform is based on local conditions in the coordinator’s neighborhood. A candidate node for becoming a coordinator now that gets actually selected for this role may be forced to remain a coordinator for an extended period of time due to network topology changes. Also, since coordinators need to stay awake all the time, this will result in wasting their energy when there is no traffic to be handled. SPAN assumes that the traffic nodes are always awake and are excluded from routing duties. In our view, this is a restrictive assumption and can limit the usefulness of this algorithm.

In GAF [14], the network is divided into virtual grids whose sizes are dependent on nodes’ nominal radio range. Each node uses its location information to determine its grid. All nodes within a particular grid have equal packet forwarding ability. Nodes can be in one of three states, active, discovery or sleeping. Nodes in a specific grid decide which node will remain awake while the rest go to sleep via a certain node ranking system that takes into consideration a node’s state, then a node’s energy level and finally node ID as a tie breaker. GAF can achieve node energy balancing within a specific grid only. This is done during the discovery period of a node that was in active state, where other nodes can take over routing duties during this period. As far as routing is concerned, GAF does not interact with the routing protocol at all, it leaves it to the routing protocol to recover from breakages that result from an active node that was involved in routing deciding to go to sleep based on GAF’s criteria. Traffic nodes are excluded from the forwarding functions and from running GAF. This is very restrictive since in reality, all network nodes are expected to share routing functions and it may not be possible to know in advance which nodes are traffic nodes. In addition, if it turns out that all nodes in the network will be sources or destinations of traffic at different points of the time, this would render GAF unusable.

In [16], the authors propose an on-demand power management framework. Energy conservation is achieved by turning on and off the radios of specific nodes in the network, which is driven by active communications within the network. Power management mode transitions are done via a soft-state timer. A node keeps track of its neighbors’ power management modes either by HELLO messages or by snooping transmissions over the air. The algorithm uses routing info to decide when to turn nodes on and off. If a certain path will be used, nodes along this path are kept awake. The drawback of using timers that get updated by packet exchange is that, if any delay is encountered due to collisions or other network non-fatal issues, the timer that controls the active state may expire prematurely leading to packet losses or delays. The authors also indicate that the way the algorithm determines the power management mode of a neighbor is through passive inference. This works via two indicators: the lack of communications in a specific period of time and packet delivery failures. In our view, this method of inference is not robust as there may be many reasons why the neighbor is not communicating other than being in a power save mode which can lead to many issues such as unnecessary delays. It also seems that the algorithm focuses on whether the neighbor is asleep or awake but does not seem to have a way to know when that neighbor will become awake if it is currently asleep. This can imply more delay and energy loss since the neighbor may be awake and idle while the sender is not aware of this.

Our protocol independent energy saving technique addresses the issues that are seen with these existing energy-efficient schemes. It allows nodes to sleep periodically in an asynchronous manner. It provides a robust method for nodes to determine if a certain node is asleep or awake. It is designed in such a way that will allow energy conservation to be achieved in a manner fair to all network nodes.

III. PROTOCOL INDEPENDENT ENERGY SAVING TECHNIQUE

As we indicated earlier, idle energy consumption constitutes a significant percentage of the overall energy consumed by the wireless interfaces of network nodes. Therefore, reducing this energy should be a cornerstone in any energy conservation
efforts. For this purpose, we introduced the PIES technique [8] where PIES stands for “Protocol Independent Energy Saving”. This algorithm addresses the main requirements that should be fulfilled by an ad hoc energy conserving mechanism which can be summarized in the following points:

- The algorithm should not have a significant impact on the network operation such as throughput.
- It should not introduce sources of significant energy consumption to the network.
- It should not introduce sources of significant traffic to the network.
- It should have a robust method of determining the mode of operation of the neighbors.
- It should be fair. Network nodes should be treated equally. This both provides the same level of service to network clients and prolongs network lifetime.
- It should be distributed. This avoids having single points of failure, bottlenecks and energy unfairness.

PIES works in conjunction with the routing protocol in use and achieves fair energy conservation through a two-pronged approach:

1. Sleep period rotation that ensures that each node within the network gets a fair share of energy savings through equal sleep periods. Therefore, nodes sleep asynchronously for a mandatory period of ST seconds followed by a mandatory wakeup period of WT seconds.

2. Providing the routing protocol with intelligence about the energy conditions of network nodes. This information can then be used by the routing algorithm to make routing decisions that help ensure fair routing duties (and therefore energy consumption) for all nodes are assigned. The information that PIES can provide the routing algorithms with can also be used to achieve alternative goals, e.g. decrease packet delivery latency, if so desired.

Rather than updating energy information upon every change in energy, PIES uses a threshold-based approach: only if nodal energy drops below a specific threshold will this information be propagated to node neighbors. This way PIES provides the routing protocol with energy threshold information about network nodes. The routing protocol then uses this information to decide on routes in such a way that will avoid the route that has the node with the smallest energy threshold. Node energy threshold is decided by the following formula:

\[ e_2 = \rho \times e_1, \]  

\[ \text{where:} \]
\[ e_1 \] is the current threshold value,  
\[ e_2 \] is the new threshold value, and,  
\[ \rho \] is the rotation factor.

PIES is modular in nature to facilitate its integration with routing protocols. It can function with routing protocols of the different categories i.e. its functionality and structure are independent of the routing protocol. It is distributed in nature and can be configured in such a way that does not impose any additional traffic or energy consumption to network operation. More details about the properties, design and analysis of PIES can be found in [8].

IV. EVALUATION OF THE TECHNIQUE

In a previous study [8], we examined the performance of PIES with the different categories of routing protocols, namely the on-demand (or reactive) routing and the proactive routing algorithms where we showed its ability to function properly with the different types of routing strategies with enhanced energy performance and without impacting the network operation performance. In this study, we continue our evaluation of PIES by examining its ability to scale with increased network traffic and population. We also compare its performance with that of the on-demand power management algorithm [16], with DSR as the routing algorithm. Through this comparison, we also show some other performance attributes of PIES such as its ability to enhance network lifetime and packet delivery performance significantly over the routing algorithm alone.

In order to evaluate PIES performance in these different conditions, we will be using simulation experiments. In these evaluation experiments, we use the ns2 simulator [5] to conduct our performance evaluation. This includes the CMU Monarch Project’s [4] wireless and mobility enhancements to ns2. In the following, we describe the simulation conditions that we generally used in our simulation experiments. Unless otherwise specified while discussing a certain experiment, these are the conditions under which the experiment was conducted. We ran our simulations for different pause times at a selected high maximum speed to test the impact on PIES operation. This represents different mobility conditions of network nodes. Each data point is an average of five simulation runs with different randomly generated mobility scenarios. For all runs, we used identical traffic models. We used the same mobility and traffic scenarios across all the cases under comparison. Table I shows the values that we used for the simulation runs. For the rotation threshold, we applied equation (1), with \( \rho = 0.9 \). However, when the energy reaches a certain low threshold (we selected 30 Joules), we switch to constant decrements of 15 Joules. In our simulations, threshold information is exchanged via the routing protocol control messages (piggybacking) as well as PIES announcements upon threshold changes. We have verified that piggybacking is sufficient for this purpose, however, we included the PIES overhead also in our simulations to get worst-case condition results.

### Table I

<table>
<thead>
<tr>
<th>SIMULATION PARAMETERS</th>
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<tr>
<td>Number of nodes</td>
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<td>Dimensions of simulation area (m x m)</td>
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<td>Initial node energy (Joules)</td>
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<tr>
<td>Simulation time (seconds)</td>
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<tr>
<td>Traffic type</td>
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<tr>
<td>Number of traffic connections</td>
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<td>Maximum node speed (m/s)</td>
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3
With these conditions, we ran our simulations using values of PIES mandatory wakeup time (WT) and mandatory sleep time (ST) pairs as specified in the relevant sections.

As far as the evaluation criteria are concerned, we measure two main aspects: the energy performance and the network operation performance. For energy performance, we measure the energy savings and the standard deviation of node energies. The standard deviation is used as means of measuring energy fairness: the lower the standard deviation, the fairer the energy consumption across nodes is. For network operation performance, we use the packet delivery ratio and packet delivery latency as evaluation measures.

In our simulations, we consider energy consumption in the sending, receiving, idle and sleep modes of operation. Table II shows the power consumption values that we used which are based on previous studies e.g. [6].

### Table II

<table>
<thead>
<tr>
<th>POWER CONSUMPTION PARAMETERS</th>
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<tbody>
<tr>
<td>Rx Power Consumption</td>
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<tr>
<td>Tx Power Consumption</td>
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<td>Idle Power Consumption</td>
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<tr>
<td>Sleep Power Consumption</td>
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#### A. Scalability of the PIES Algorithm

In this section, we examine the ability of the PIES algorithm to scale with the increase of the network population as well as with the increase of traffic data rate. The goal here is to measure the ability of PIES to continue to deliver operational performance that is comparable to that of the routing protocol alone, and energy performance that is superior to that of the routing protocol alone for bigger networks.

1) **PIES Scalability Performance with Higher Network Population:** We performed this experiment with networks that have 50, 75 and 100 network nodes, respectively. We used the mobility scenarios based on this number of nodes, and the rest of the simulation conditions are kept the same. We used AODV as the routing protocol. For PIES, we used ST/WT values of 0.25/0.5 with ST and WT measured in seconds.

The increase of network nodes increases possibility of collisions with each network node trying to advertise its presence according to the routing protocol strategy, in this case AODV HELLO messages. Also, the possibility of more routes and route replies to requests increases, hence increasing the traffic load on the network.

As far as energy performance is concerned, we see from Fig. 1 that PIES in this case resulted in around 30% energy savings over AODV alone for this ST/WT pair for all cases. As we have demonstrated in [8], the level of energy savings is increased with the increase of the ST:WT ratio. The standard deviation trend shown in Fig. 2 is also more or less the same as in all cases, which indicates increased fairness with PIES enabled (increased fairness is indicated by the decrease of the standard deviation of node energies). Looking at the network operation performance, we see that the packet delivery ratios are comparable in the case when PIES is enabled to that where AODV is functioning alone, see Fig. 3. We notice a slightly better PDR performance in general in all cases than in the case with 50 nodes due to the fact that more nodes are available which results in more routes to destinations due to the denser nature of the network. By examining the packet delivery latency trend in the case where PIES is enabled and where PIES is disabled, we find that the latencies in case of PIES are higher than with AODV alone due to the sleep times imposed on the nodes. The difference is, however, narrower as the number of nodes increases and this is particularly clear between the 50 node case and the other two cases, see Fig. 4. We attribute this again to the denser network that enables shorter routes with more possibilities of nodes awake on these routes which can reduce the time a route is discovered and used.

From this experiment, we see that PIES continues to perform well as the network node population increases. In fact, it shows some improvement with regard to the packet delivery latency as we explained above.

2) **Scalability of PIES with Different Traffic Rates:** In this experiment, we measure the performance of PIES as the network traffic increases. In order to perform this evaluation, we use the same network conditions as indicated previously but with several data rates. At each of the chosen data rates, we measure both the energy performance and network operation performance and compare the case when PIES is enabled with that when it is not. We used AODV as the routing protocol and ran the simulations for the case where pause time = 600 seconds, i.e. with no motion.
From Fig. 5, we see that the energy savings of PIES over AODV alone is consistent regardless of the traffic rate. This is also generally the case as far as energy fairness is concerned, which is evident from the trend shown by Fig. 6.

Considering network operation performance, Fig. 7 and Fig. 8 show the packet delivery ratios and packet delivery latencies respectively with the different traffic send rates.

From these figures, we see that the packet delivery ratio performances when PIES is enabled and when it is disabled are identical. At a very high rate, 15 Kbps, we start seeing a slight drop when PIES is enabled. This drop is due to interface queue overflow that occurs as the data rate increases together with the fact that PIES causes packet buffering while nodes are asleep. It is worth mentioning that when we increased queue sizes, we were able to lower this drop which is already very small. We have not reflected this in the results, however, since this increase in the queue size is not needed in the case of the routing protocol alone. As for the packet delivery latencies, we see that the difference is consistent for low, medium and relatively high data send rates.

As the traffic data rates get higher, we see that the latencies with PIES enabled start to increase at a higher rate. This can be attributed to increased contention at the communication channel due to the buffered traffic that results from nodes having been in sleep state combined with the already constantly high traffic rate.

From this experiment, we see that the PIES performance is consistent with the higher network traffic both from energy and network operation points of view. As the traffic becomes quite high, the PIES-induced latency increases further.

### B. Comparing PIES with the On-demand Power Management Algorithm

In this section, we compare the performance of the PIES algorithm with that of the on-demand power management algorithm [16]. We have selected this algorithm for our comparison since it also addresses the main source of energy waste, idle energy consumption, and its operation is based on a realistic network model (i.e., all nodes can participate in routing duties, unlike GAF and SPAN, for example). The on-demand power management algorithm selects a routing backbone that remains turned on, based on the route discovery strategy of the routing protocol. We use DSR [9] as the routing protocol in this comparison experiment. DSR is an on-demand (reactive) routing protocol.

#### 1) Qualitative Comparison

In order to pave the way for the experimental comparison between the two algorithms, we first perform a brief comparison between the functionality of both the PIES and the on-demand power saving algorithm which we reviewed in Section II. Table III compares the main features of both algorithms.

We see from this comparison that PIES provides a method to determine the node sleep state that is far more robust than that of the on-demand power saving algorithm. Also unlike the on-demand power saving algorithm, PIES has a modular architecture that enables it to fit easily with existing routing algorithms. Moreover, this structure does not need to be
changed with the change of the routing algorithm in use. PIES also does not require supporting broadcast messages to be sent separately, which means that it does not impose additional traffic burden on the network.

2) Performance Evaluation: In order to compare the operation of PIES to that of the on-demand routing protocol, we selected the ST/WT pair value for PIES to be equal to 0.3/0.5. This is to achieve energy savings that are comparable to that of the on-demand algorithm in static scenarios, so that we do not focus the discussion solely on the amount of achievable energy savings.

We measured both the energy performance and network operation performance in our comparison. As far as energy performance is concerned, and for the selected ST/WT value of PIES, we found that PIES results in consistent power savings of about 35% regardless of the mobility conditions of network nodes. The savings that PIES provides are higher than those of the on-demand power management scheme until the network becomes almost static. At static conditions, the on-demand algorithm provides marginally higher savings (about 37%), see Fig. 9. In [8], we have shown that PIES can provide even higher savings, including in the static case, if we increase the ST:WT ratio.

Considering energy consumption balance and fairness, the on-demand power management algorithm does not pay any attention to this aspect. It seems that the nodes that are on some routes are severely penalized and are kept on for most if not all time while the other, less strategically positioned nodes, are allowed to enjoy extensive energy savings. This strategy can be detrimental to network operation in such cases where some nodes that are critical to the operation of the whole network are over-utilized and hence get depleted much faster than others. In the case of PIES, it shows energy performance that is fairest considering DSR alone and DSR with on-demand power management, see Fig. 10. As far as packet delivery is concerned, both PIES and the on-demand algorithm seem to perform comparably to DSR alone especially at lower mobility, see Fig. 11. Considering packet delivery latency, we found that the on-demand power management algorithm performs clearly better than PIES, see Fig. 12. The reason is that it keeps the nodes that are on active routes always on with no attention given to conserving their idle energy. Therefore, it can provide better packet delivery latency performance at the price of wasting energy and in an unbalanced manner for some nodes.

3) Effect on Network Lifetime: In order to complete the comparison, we also examined the performance of both PIES and the on-demand power saving algorithm under reduced initial energy conditions. For this purpose, we performed the above experiment with initial node energies of 300 Joules. We examined the effect on network lifetime, which we define as the time until the network operation comes to a complete stop with all the nodes vital to the operation failing. Fig. 13 shows the results. From this figure, we see that PIES performs clearly better than the on-demand power saving algorithm even in the static network case.

Since network lifetime extension alone does not give a sufficient indication about the network health in low energy conditions, we also examined the effect on network capacity. For this, we measured the number of delivered payload packets for both PIES and on-demand power saving relative to DSR alone. Fig. 14 shows this comparison.

The results are rather interesting. It seems that, despite the

<table>
<thead>
<tr>
<th>Comparison aspect</th>
<th>PIES</th>
<th>On-demand</th>
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<tbody>
<tr>
<td>Use of broadcast messages</td>
<td>Optional</td>
<td>Beacon messages</td>
</tr>
<tr>
<td>Dependent on the nature of the routing protocol</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Method of determining neighbor sleep state</td>
<td>Deterministic</td>
<td>Inference</td>
</tr>
<tr>
<td>Energy fairness by design</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Modularity</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Routing protocols it can operate with</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>Separation between traffic nodes and routers</td>
<td>No</td>
<td>No</td>
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Fig. 7. Packet delivery ratios with different traffic rates

Fig. 8. Packet delivery latencies with different traffic rates

TABLE III
COMPARISON BETWEEN PIES AND ON-DEMAND POWER SAVING ALGORITHM
longer lifetime that the on-demand algorithm gives over DSR alone, the corresponding increase in packet delivery is quite low especially at high mobility conditions. The increase in delivery is well below 10% at its highest point. In the case of PIES, the increase in packet delivery over DSR in these conditions is considerably higher and reaches above 60% in the static case. In high mobility conditions it is still high and is close to 50%.

From this comparison, we see that overall, PIES performs clearly better than the on-demand power saving algorithm. It provides consistent power savings regardless of network mobility conditions. It does so in a fair manner to all network nodes which results in healthy network conditions for a considerably longer period of time over the on-demand power saving algorithm.

V. CONCLUSIONS AND FUTURE WORK

In this study, we presented some simulation results to demonstrate the functionality of the PIES algorithm and its effect on the energy and network operation performance. First, we showed that PIES performs well with increased network population. Its energy performance is consistent and its network operation performance remains comparable to that of the routing algorithm alone with the increase of the number of network nodes. We then showed that PIES performance is also consistent with the increase of network traffic. Packet delivery latency starts to increase noticeably when very high traffic is induced into the network.

We also performed qualitative and experimental comparisons with the on-demand power saving algorithm with DSR as the routing protocol. Overall, PIES showed superior results to those of the on-demand routing protocol and was able to expand network lifetime far beyond the on-demand power saving case. It was also able to show a much better packet delivery performance under limited battery energy conditions.

When we consider these results, we find that PIES produces good network operation performance results with substantial energy savings and network lifetime extension. This is done while achieving energy fairness which is our primary target. PIES also integrates nicely with existing routing protocols and does not impose any unrealistic conditions on network operations (e.g. separating traffic nodes from routing nodes). Based on the results presented in this paper, we will investigate using the information that PIES can provide to decrease the packet delivery latency that is introduced by PIES, without affecting its energy performance. We will also investigate the possibility of integrating PIES with algorithms that use energy-efficient routing strategies and measure the resulting combined effect.

REFERENCES

Fig. 10. Standard deviation for node energies: (a) DSR alone and with PIES, (b) DSR alone and with the On-demand power saving algorithm.

Fig. 11. Packet delivery ratio performance with PIES and on-demand power management.

Fig. 12. Packet delivery latency for DSR, PIES and on-demand power management.

Fig. 13. Percentage increase in network lifetime for PIES and on-demand power saving algorithms over DSR alone.

Fig. 14. Percentage packet delivery increase for PIES and on-demand power saving over DSR alone in reduced energy conditions.