

# Exploiting Overhearing: Flow-Aware Routing for Improved Lifetime in Ad Hoc Networks

Nirisha Shrestha, Bernard Mans  
Department of Computing, Macquarie University  
Sydney, NSW 2109, Australia  
Email: {nirisha, bmans}@ics.mq.edu.au

## Abstract

*For nodes of mobile ad hoc networks, energy is a scarce resource that can be quickly depleted by communications. Moreover, due to the nature of wireless communication medium, nodes can waste a substantial amount of energy by overhearing packets in their neighborhood, most of which may not be meant for them. The overall impact of overhearing is not well-studied: many of the schemes claiming to be energy-efficient neglect this cost by only focusing on energy costs due to local traffic. In this paper, we propose that nodes exploit overheard packets to gather awareness of current neighboring flows and adapt their local routing dynamically. By combining this awareness with battery-aware routing metrics, which includes the battery levels of the neighbors, we introduce various routing schemes that increase the network lifetime.*

## 1. Introduction

Often as a requirement of portability, wireless nodes in MANET have limited energy resources like batteries that can be quickly depleted by expensive wireless communications (including the energy cost of handling traffic for other nodes). In recent years, a large body of work considered the energy consumed, but only at the nodes participating in the existing flows. For MANET, a single communication packet can affect not only the sender and the receiver, but also all the nodes within the communication region of the sender. The important fact to notice is that, in addition to interference, this substantially increases the energy consumption at nodes overhearing this packet not meant for them [4, 7], to the extent that a node's battery can be completely depleted without being involved in any flow.

In this paper, we propose to exploit the (unavoidable) cost of overheard packets (as they provide some knowledge that help gather awareness of current neighboring flows) to

adapt their local routing dynamically. Indeed, it is arguable that the overhearing effect grows with the number of flows in the network. We first discuss some complexity results (in Section 2.1) and then discuss how we can use Signal-to-Interference Ratio (SIR) and the energy consumption model in [3] to study whether a more traffic-conscious routing scheme works better in improving the energy-efficiency of the network in Section 2.2 and Section 2.3 respectively. A cost based on locally available information about flow and neighborhood is presented in Section 2.4. We then evaluate these schemes by comparing them with the performance of energy-aware routing in [9] in Section 3.

## 2. Using Flow Information for Routing

### 2.1. Complexity considerations

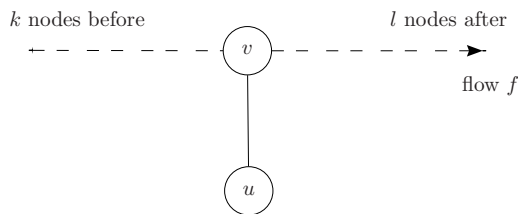
Finding a simple unicast path that guarantees enough remaining energy locally at each node in the network is an NP-complete problem when reception energy is included [2]. As per a similar complexity result with overhearing [5], the proof is based on the reduction to the Forbidden Pair Problem and could be trivially adapted to show that minimizing the number of overlapping flows (in their communication region) is NP-Hard, even if the complete topology and the set of flows are known. This is not surprising as it is known that the simpler problem of minimizing the number of overlapping flows without considering the wireless communication region is NP-hard. Indeed, this problem is easily reducible to the following *Maximum Disjoint Connecting Paths* problem [1]: **Instance:** A Multigraph  $G = (V, E)$  and a collection of node pairs  $T = \{(s_1, t_1), (s_2, t_2), \dots, (s_k, t_k)\}$ . **Solution:** A collection of edge disjoint paths in  $G$  connecting some of the pairs  $(s_i, t_i)$ , i.e. sequences of vertices  $u_1, u_2, \dots, u_m$  such that, for some  $i$ ,  $u_1 = s_i, u_m = t_i$ , and for any  $j$ ,  $(u_j, u_{j+1}) \in E$ . **Measure:** The number of vertex pairs  $(s_i, t_i)$  that are connected by the paths.

## 2.2. Measuring Traffic in the Neighborhood

**SIR:** In theory, traffic can be estimated using SIR or Bit Error Rate (BER) at the receiver, which can give a good instantaneous measurement of the link quality between two nodes. However, this measurement can be done only at the receiver, and not at the sender where the decisions about the next hop are made. The only related parameters available to the sender are properties like packet loss rate or the retransmission count for a particular receiver but these measurements can be inaccurate. In order for the sender to have a more precise knowledge about the channel status at the receivers, the SIR/BER values at the receiver need to be fed back to the sender with the help of periodic hello or similar packets. Some discrete sampling and averaging of the SIR/BER are required for each interval, but averaging SIR may not give an accurate overview of link status, specially when there is random bursty traffic/noise.

**Flow Count:** Due to this inaccuracy in measuring SIR, the number of flows passing through a node is used in this paper as an alternative measure of the traffic conditions in the node. The averaged value of this number for a node and its neighbors over a period can give a good estimation of the traffic conditions around the node. It should be noted that the use of number of flows is valid only when the number of bytes sent or received is of the same order for each flow. In the next two sections, we first evaluate the lifetime of the network when energy consumption at a node due to flows in and around it, is used to make routing decisions. Then, we show that by utilizing only local knowledge about the number of flows and the neighborhood size as a metric, that the improvement in network lifetime is very close to the case when using more granular metric based on energy due to the number of flows in the neighborhood.

## 2.3. Approximating Energy Consumption due to Flows



**Figure 1. Effect on node  $u$  due to node  $v$  in flow  $f$**

In this section, we use the energy model given by Equation 1 below to approximate the total energy consumption at a node due to the flows in and around it as introduced in [3].

$$E_{u/v} = \mathbb{1}_{k>0}(\mathbb{1}_{v=u}E_{T_{ack}} + \mathbb{1}_{v\neq u}E_{R_{ack}}) + \mathbb{1}_{l>0}(\mathbb{1}_{v=u}E_{T_{pck}} + \mathbb{1}_{v\neq u}E_{R_{pck}}) \quad (1)$$

where

$$\begin{aligned} E_{u/v} &= \text{energy spent at node } u \text{ due to node } v, \\ E_{T_{ack}} &= \text{energy spent for transmission of an ACK packet,} \\ E_{T_{pck}} &= \text{energy spent for transmission of a data packet,} \\ E_{R_{ack}} &= \text{energy spent for reception of an ACK packet,} \\ E_{R_{pck}} &= \text{energy spent for reception of a data packet,} \\ \mathbb{1}_p &= \begin{cases} 1 & \text{if } p \text{ is true,} \\ 0 & \text{otherwise.} \end{cases} \end{aligned}$$

The total energy spent at a node is the sum of the energy spent at it due to all the nodes in the reception and interference area of this node. Thus, in this model, the transmission and reception costs are included if the node belongs to a flow, and reception costs are included if it is near the flow.

When the node under consideration,  $u$  is neither a source nor a destination of a flow (such that both  $k$  and  $l$  in Equation 1 are greater than 0 for all flows), we have an upper bound in the energy consumption due to the flows in a node (i.e., a worst case scenario):

$$E_{u/v} = \mathbb{1}_{v=u}(E_{T_{ack}} + E_{T_{pck}}) + \mathbb{1}_{v\neq u}(E_{R_{ack}} + E_{R_{pck}}) \quad (2)$$

Let  $F(u)$  be the number of flows passing through node  $u$ , and  $F_i(u)$  be the number of flows in the nodes in  $u$ 's carrier sensing region, then:

$$E_u = F(u) \times (E_{T_{ack}} + E_{T_{pck}}) + F_i(u) \times (E_{R_{ack}} + E_{R_{pck}}) \quad (3)$$

Since the assumption is that the flows do not start or end at node  $u$ ,  $F_i(u)$  includes the  $F(u)$  flows that are continued before and after node  $u$ .

We also assume that this number of flows in the carrier sensing range is approximated by the number of flows in the one-hop neighborhood,  $N(u)$ , and the two-hop neighborhood,  $N_2(u)$ . Our simulations show that the large overhead required to collect information about three hops and beyond is not justified by the improvement brought about by the knowledge of such information. Additionally, finding the exact carrier sensing region is a non-trivial task. Moreover, only its strict two-hop neighborhood  $N_{2s}(u)$  (the neighboring nodes of the neighbors of  $u$  which are not already neighbors of  $u$ ) is considered. Then, the total energy at node  $u$  due to the flows in and around it is given by

$$E_u = F(u) \times (E_{T_{ack}} + E_{T_{pck}}) + \left[ \sum_{v \in N(u)} F(v) + \sum_{w \in N_{2s}(u)} F(w) \right] \times (E_{R_{ack}} + E_{R_{pck}}) \quad (4)$$

In order to make the routing more conscious about the energy consumption in the constituent nodes of the routes,

this energy consumption measurement, in combination to the node's battery reserve  $B(u)$ , which is the node's current battery level,  $b_c(u)$ , expressed as a percentage of the initial battery capacity,  $b_i(u)$ , (*i.e.*,  $B(u) = \frac{b_c(u)}{b_i(u)}$ ), is then used as a routing metric. Hence, the cost can be calculated as shown in Equation 5.

$$Cost = \frac{1}{B(u)} (1 + E_u) \quad (5)$$

With this cost,  $E_u$  measures the effect of the flows in the node and its surroundings have on node  $u$  itself, while  $B(u)$  avoids nodes with low battery reserves. If the battery reserve is high, even if the average energy consumption rate is more, the cost stays lower, but as the remaining energy decreases, the energy consumption rate has more effect, discouraging routing through nodes which already have a large number of flows affecting their energy consumption.

## 2.4. Using Local Flow-Aware Routing

Instead of sending the flow information in the hello packets, in order to evaluate the reception-aware cost, the routing protocol in this section aims to reduce the interfering receptions due to the flow locally. For this, each node locally calculates the number of interfering receptions it can trigger, which is given by the total number of flows passing through it ( $F(u)$ ), multiplied by the total number of its one-hop and strict two-hop neighbors. For this type of cost, the number of flows does not need to be sent to the neighbors because the cost will be calculated locally according to the number of flows in the node itself. So the cost is proportional to  $F(u) \times (|N(u)| + |N_{2s}(u)|)$ . As the cost also needs to be aware of the battery reserves of the nodes being considered, the energy-aware flow-based cost could be:

$$cost = \frac{1}{B(u)} [1 + k \times F(u) \times (|N(u)| + |N_{2s}(u)|)] \quad (6)$$

where  $k$  is a constant such that  $k > 0$ .

However, it was found through simulations that the performance of including granular details like the size of the entire two-hop neighborhood increases the cost factor of a node unnecessarily without bringing any further improvement, whereas the one-hop neighborhood is enough to reflect the traffic conditions around the node. Hence, the final equation for the flow-based routing metric is given in Equation 7 below.

$$cost = \frac{1}{B(u)} [1 + k \times F(u) \times |N(u)|] \quad (7)$$

In this type of cost, the node calculating the cost is more aware of what is happening in the neighborhood, and how

its transmissions can affect these neighbors. Due to the parameter  $N(u)$ , nodes with fewer neighbors are encouraged,  $F(u)$  favors nodes with less flows, while the use of  $B(u)$  discourages the nodes with low energy reserves.

## 3. Performance Analysis and Validation

### 3.1. Simulation Settings

The flow-aware energy-efficient routing schemes have been evaluated with the help of the ns-2 simulator with the OLSR plugin [6]. From 32 to 100 nodes are randomly placed in a square field of 1000m  $\times$  1000m. For each network size, 10 simulations are run for 200 seconds, each with 4 to 12 CBR flows, with 2 kilobyte packets generated at 250kbps, started after 6 seconds of simulation time. RTS/CTS is turned off. The idle energy consumption is set to zero, and the power consumption (0.582W and 0.1W for transmission ( $P_{T(xy)}$ ) and reception ( $P_{R(xy)}$ ) respectively) is taken as the difference between their manufacturer specified values and the idle energy consumption. The values for power consumption are taken for the OriNOCO PC Gold as measured in [8]. Initial battery reserve,  $b_i(u)$  [9] is taken as 15J and the energy deficiency threshold,  $E_{th}$  [9] is 25%.

The performance of the following schemes are evaluated in the presence of different number of flows:

1. **802.11:** This is IEEE 802.11 running OLSR without modifications.
2. **eRouting:** This scheme is the reception-aware energy-efficient routing based on the combined routing metric presented in [9] and also included as Equation 8 below:

$$C(u) = \frac{1}{B(u)} \left( 1 + k \times \frac{D(u)}{N(u)} + j \times N(u) \right) \quad (8)$$

where  $E_{th}$  is the energy deficiency threshold,  $D(u)$  is the number of battery deficient neighbors of node  $u$ ,  $B(u)$  is the current battery reserve, while  $k$  and  $j$  are constants, chosen to be  $N_{exp}$  and 0.1 respectively.

3. **e-flowRouting:** This routing scheme uses the current battery reserve, and the energy consumption due to the flows in the node as well as its neighborhood as its routing metric. According to the value of  $P_{T(xy)}$  and  $P_{R(xy)}$  given above, the various elements for energy are calculated as in [3] to be 4.877 mJ, 0.838 mJ, 0.176 mJ and 0.03 mJ for  $E_{T_{pck}}$ ,  $E_{R_{pck}}$ ,  $E_{T_{ack}}$ , and  $E_{R_{ack}}$  respectively.
4. **flowRouting:** This is the flow-based routing, based on the cost in Equation 7 (with  $k = 0.1$ ).

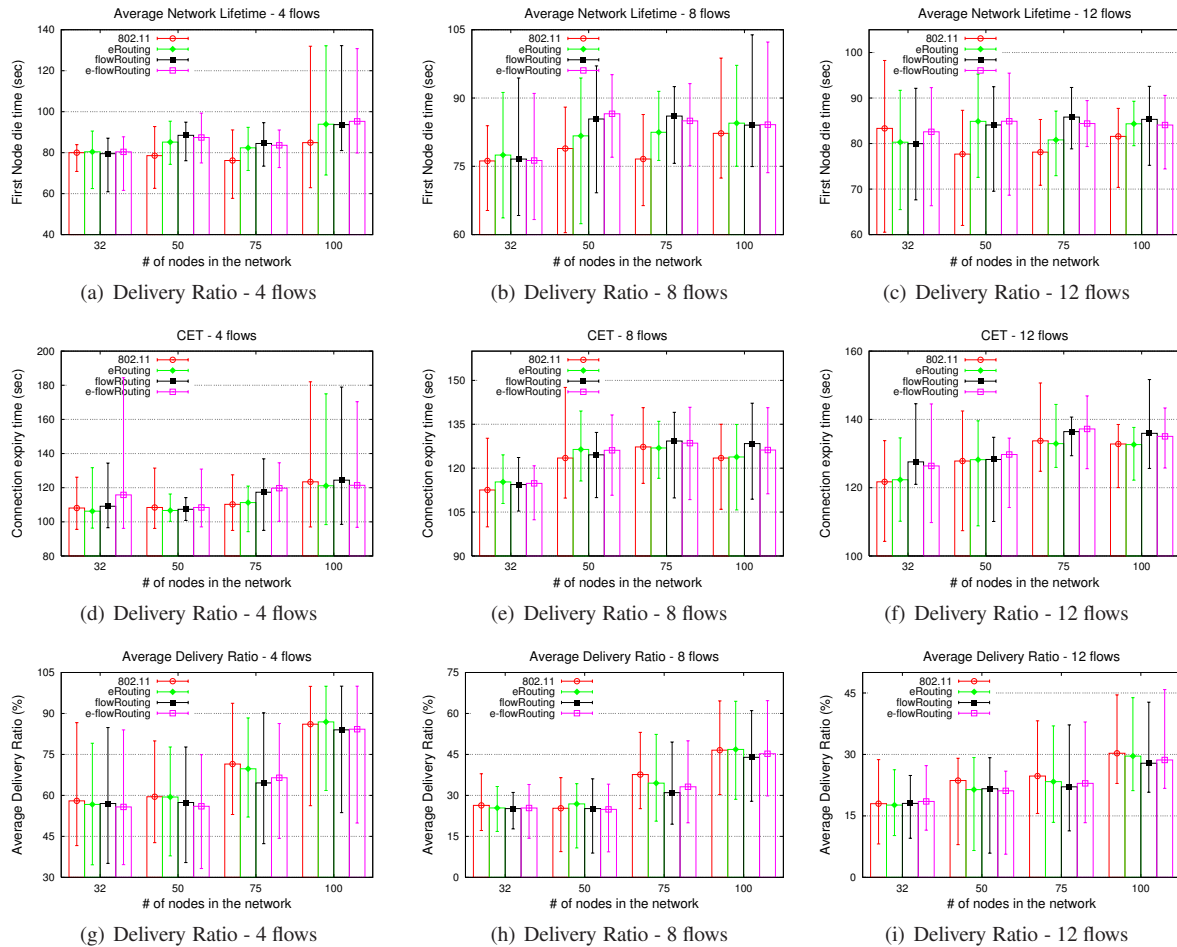


Figure 2. Network lifetime and connection expiry times and average delivery ratio

## 3.2. Results and Analysis

### 3.2.1 Network Lifetime and Energy Consumption

The time when the first node in the network runs out of its battery is taken as the first measure of network lifetime. In Figure 2, it is observed that for all the three energy-aware schemes (*eRouting*, *flowRouting* and *e-flowRouting*), there is an increase in the network lifetime with the increase in the number of flows in the network, except for the 32-node network (where too few alternatives for routes are present). As the number of flow increases, *802.11* remains simple, yet robust for such sparse networks. It is observed that for *eRouting*, the increase in the network lifetime is maintained with the increase in the number of flows in the network, again except for the 32-node network. However, the flow-based routing schemes are found to increase the lifetime further in most of the cases, particularly in denser networks with higher number of flows, while the lifetime is similar to that of *eRouting* in sparser networks. For example, in the presence of 12 flows, *eRouting* brings about an increase in

the lifetime of only about 3%, while the flow-based schemes increase the lifetime by about 10%. When comparing between the two flow-based routing schemes (see Figure 2), the improvement in the lifetime due to the two schemes are closely matching each other, with the *flowRouting* slightly increasing the lifetime compared to *e-flowRouting* in denser networks with higher number of flows.

As the flows were assumed to be continuous in this paper, an equally important measure of the network lifetime is the connection expiry time (CET). This is the time when the packet generation for a flow stops due to the source depleting its battery, or due to the lack of a route (disconnection). In order to measure the worst case scenario, the average time when the final flow in the network expires is presented in Figure 2. It is observed that CET is slightly higher (up to nearly 10 seconds) or similar to *802.11* in almost all of the cases for the flow-based routing, while *eRouting* has a lower connection expiration time than *802.11* in a few cases. In terms of energy consumption, all the energy-aware schemes consume similar amount of en-



ergy as the *802.11* scheme while the connections in *802.11* remain active. Since the connections last slightly longer for the energy-aware schemes, the energy consumption increases even after the connections expire in *802.11*. For the same reason, we observed that the flow-aware schemes have a higher final energy consumption than *eRouting*.

### 3.2.2 Throughput and latency

The average packet delivery ratio for the various schemes is shown in Figure 2. In general, the delivery ratio of the energy-aware schemes is slightly reduced in comparison to *802.11*, with the difference higher for the flow-based schemes. The reduction in the throughput is mainly due to the fluctuations in the routes, as the nodes recalculate their costs locally at each hop and redirect the packets to what they see as an energy-efficient next hop. To prevent frequent fluctuations in the routes, an application of a smoothing factor to the node costs shows a better delivery ratio, although it still does not outperform *802.11*. However, the delivery ratio does not decrease drastically for any of the energy-aware schemes, and remain within a reasonable difference. In average, the latency of the packets is higher for the energy-aware schemes, especially near the CET, when the number of energy deficient nodes are higher, such that these routing schemes more actively choose longer paths with more hops in order to use more energy-efficient routes. The latency is observed to be higher for denser networks, mainly because these networks have more alternate routes to choose from, and hence for the energy-aware schemes, the nodes have higher chances of taking longer, more reception energy-efficient paths. The increase in the number of hops however also increases the probability of collisions, and hence has contributed to the decrease in the throughput of the energy-aware schemes as well.

## 4. Conclusions

In this paper, we combine reception-awareness and flow-awareness to accurately account for the interference due to traffic in and around a node.

Evaluations through simulations show that all our energy-aware schemes increase the lifetime of the network in most of the cases, except in sparse networks with high traffic load (due to lack of alternative paths). In denser networks, the flow-based schemes have a higher increase in the network lifetime in comparison to the *eRouting* scheme which is not flow-aware. In addition, the connection expiry times for the flow-aware routing are observed to be higher as well, verifying the positive impact of the flow-awareness. However, it is observed that due to the highly dynamic nature of the wireless networks, the best path as chosen locally does not always remain the most efficient as

the packets travel further in the route and the conditions at these intermediate nodes change. Also, as the path length may increase further while trying to use a more energy-efficient path, there is an increased probability of collisions and packets loss which induces a general decrease in the delivery ratio of all the energy-aware schemes, though the decrease is not drastic. Hence, reception-aware models which are aware of the flows in the network give an accurate account of the interference impact of the traffic in the network and hence are more effective in improving the energy-efficiency as well as, to a lesser extent, other performance indicators like throughput and latency.

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