Energy Efficiency of Ad Hoc Wireless Networks with Selfish Users

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ABSTRACT

We deal with energy efficiency and quality of service provisioning in multihop ad hoc wireless networks. We assume that each node generates traffic for some other node in the network and that the available routes between each source-destination pair are known. Each source randomly selects one of the possible routes and asks the intermediate nodes on the route to relay traffic. Since energy is a valuable resource, intermediate nodes may not wish to consume their energy to carry the source's traffic. However, if every node behaves 'selfishly' and refuses to cooperate, network throughput may be drastically reduced. In this paper, we investigate the tradeoff that exists between energy consumption and blocking probability of a session, and study the ability of the network at guaranteeing a low energy consumption to users that want or need to be selfish. We define a parameter, called sympathy, which reflects the level of selfishness/altruism of the nodes. We propose two different strategies, which govern the node behavior, and compare their performance as sympathy is varied.

1 INTRODUCTION

In recent times, we have witnessed significant research in the area of ad-hoc networks. These networks are very attractive since they provide ubiquitous connectivity without the need for fixed infrastructure.

We consider an ad hoc network composed of mobile nodes, which communicate over the wireless channel. Nodes are battery-powered; thus energy is a precious resource, that has to be carefully used by the nodes in order to avoid an early termination of the their activity. A key feature enabling connectivity in the network is the store and forward concept, i.e., a node can transmit packet traffic to a far off destination by using relay nodes. This concept not only results in increased connectivity, but also leads to energy savings since relaying information between nodes may result in lower power transmission than communication over large distances [1, 2].

Most of previous work on ad hoc networks [1, 2, 3, 4] has implicitly assumed that nodes are cooperative; that is, whenever a node receives a request to relay traffic, it always does so. This ignores the user viewpoint [5]. Consider, for example, an airport lobby or a conference room with a gateway node to the Internet. A number of users might form an ad-hoc network to access the gateway node. The user physically near the gateway node will end up relaying most of the traffic; however, since this user views his energy resource as being limited by battery life, it may not feel inclined to relay traffic for other users. From this perspective, the assumption of a cooperative network is not always justified. On the other hand, if no user cooperates in relaying traffic, it will result in a loss in connectivity and possible inability of the users to convey traffic to the destination.

In this paper, we assume that network nodes may have different behavior because of their application needs or their physical constraints. We assume connection-oriented traffic and consider as performance metrics the nodes' energy consumption and the connection blocking probability. The objective is to allow users to be selfish if they need to be so, and study the impact of their behavior on the system performance.

The first aspect that we investigate is the tradeoff that exists between the energy expenditure of a node and the probability that its request for a traffic connection is declined by the network due to the non-cooperation of the relay nodes. If we assume that each user wishes to maximize his throughput, it may be in his best interest to be cooperative and relay traffic for another user. He may do this in the hope that when he attempts to transmit at a later time, the favor will be returned and his connection request will not be blocked. This however, implies that the user will have to spend part of its energy resource for relaying traffic of other users.

The second aspect that we explore is the ability of the network to guarantee low energy consumption levels for users who want or need to be 'selfish'. For instance, one can think of network pricing schemes that charge more for users that want to use their energy resources more sparingly.

The paper is organized as follows. In Section 2, we review previous work on the problem of nodes cooperation in ad hoc wireless networks. In Section 3, we propose two novel policies which regulate the user interaction and can be implemented in a distributed fashion. We call the two strategies RANDOM and PAY-IT-FORWARD. In Section 4, we investigate their performance in the case where all users in the network have the same behavior, as well as when some users are more selfish than others. Finally, in Section 5 we conclude the paper and discuss aspects that will be subject of future research.

2 RELATED WORK

The problem of non-cooperative nodes has been addressed previously in [5, 6, 7, 8].

In [6], non-cooperative nodes are viewed as malicious, and methods to identify misbehaving users and to avoid routing through these nodes are presented.

In [5, 7, 8], the idea that users may not want to cooperate because of their battery constraints is introduced and simple rules are proposed, which can be used to determine on a packet-by-packet basis whether a user should forward other nodes' traffic or not. In particular, in [5, 7] the authors propose a method based on the introduction of a virtual currency, the so-called *nuglets*. Every network node has an initial stock of nuglets. Either the source or the destination of each traffic connection use nuglets to pay the relay nodes for forwarding data traffic. The cost of a packet may depend on several things, such as the required transmission power and the nodes battery status. Packets sent by or destined to nodes that do not have a sufficient amount of nuglets are discarded. Notice that when the source nodes are charged for the packet price, it is likely that the amount of paid nuglets is under- or over-estimated, since traffic sources can not know the exact packet cost. However, if the destination nodes are charged for the packet forwarding, sources might overload the network with useless data. A hybrid approach would solve this problem, although its implementation seems to be more complicated. In [8], a simpler mechanism is proposed, which makes source nodes pay as many *battery units* as the estimated number of nodes on the path to the destination, and makes relay nodes earn as many battery units as the number of forwarded packets.

Looking at the approaches above, we identified the following critical aspects, that still need to be solved.

i) The cost and the payment for traffic forwarding on a packet-by-packet basis imply a significant communication overhead and implementation complexity.

ii) The possibility of having different classes of users or user behaviors should be considered.

iii) A node may be unable to get any reward due to its peripheral location with respect to a preferred destination (e.g., a gateway node connected to the fixed network). This may lead to unfairness in routing the nodes traffic.

The strategies that we propose aim at addressing these issues.

3 STRATEGIES FOR AN EFFICIENT USER INTERACTION

We consider an ad-hoc network of N nodes, which are uniformly spread over a circular area of unit radius. Any node can initiate a traffic session. Session requests are randomly generated at the network nodes and traffic destinations are selected among the network nodes according to a uniform distribution. Each session is characterized by two parameters, namely the file size and the transmission rate. The file size is chosen according to a geometric distribution, while the transmission rate is equiprobably selected from a pre-defined set of transmission rates.

We assume that for each source-destination pair, (s,d), the set of available routes, $\mathcal{R}(s,d)$, is known. Let us define as R_{max} the maximum number of routes existing between each source-destination pair, and indicate with $N(r)$ the number of nodes on route r, $r \in \mathcal{R}(s,d)$. Let us denote by $p_{tx}(k,r)$ the power spent by node k in transmitting to the next node on route r; for the sake of simplicity, we assume that this parameter depends only on the distance between the transmitting and the receiving node. Then, we associate with each route r an energy cost given by

$$\textit{energy cost} = \sum_{\substack{k \in r \\ k \neq d}} p_{tx}(k,r). \tag{1}$$

When a traffic session is generated at the source node s toward destination d, s selects the route in $\mathcal{R}(s,d)$ that has the minimum energy cost and requests the nodes in the route to relay its traffic to d for the whole duration of the session. A relay node has the option to either accept or refuse the request. If the connection request reaches node d, it means that all nodes along the selected route are willing to support the traffic session, and an acknowledgment is sent to the source by d. On the contrary, if any node on a particular route refuses to relay traffic, it transmits a negative acknowledgment back to the source. As s receives a negative acknowledgment, it sends the request to the nodes in the route that has the following best energy cost. If all routes are unavailable, then we say that the session request is blocked. We highlight that nodes along a valid route are always forced to forward messages carrying either a session request or an acknowledgment.

The decision taken at a relay node depends on the following factors.

i) The total amount of data that the source intends to send to its destination, since cooperation from the nodes belonging to the selected route is required for the entire duration of the session rather than on a packet-by-packet basis as in [5, 7, 8].

ii) The strategy that is adopted.

iii) The behavior of the nodes.

In order to model users with different behavior, we associate with each node a parameter called *sympathy*, taking values in the range $[0,1]$. This parameter intuitively reflects how willing a node is to relay traffic for other nodes: a value of 0 reflects extreme selfishness, while a value of 1 reflects extreme altruism. The value of *sympathy* may depend on the energy constraints of the wireless node, on its location in the network area, or on the particular user's needs. In the following, for each source-destination connection, we denote by *sympathy*(k, r) the *sympathy* level associated with the k-th node in route r, $r \in \mathcal{R}(s, d)$.

In order to explore the trade-off between energy efficiency and blocking probability for users with different behavior, i.e., value of *sympathy*, we consider two strategies: the RANDOM and PAY-IT-FORWARD strategy.

The RANDOM Strategy. Let us assume that a session is generated for the source-destination pair (s, d), and that the available routes $\mathcal{R}(s, d)$ are stored at s in increasing order based on their energy cost. According to the RANDOM policy, when the generic k-th node in route r receives the session request from s, it accepts the request with probability *sympathy*(k, r). The algorithm executed at the source and at the relay nodes are reported below.

Source Algorithm

1. Set $r = 1$
2. /* Loop over all routes available to the source */
   While $r \leq R_{max}$
      Send session request on route r
      If r accepts request
        Break from while loop
      Else $r = r + 1$
   End While
3. If $r \leq R_{max}$ Transmit on route r
   Else Session is blocked.

Upon a session request arrival, the generic k-th node in route r acts as follows.

Relay Node Algorithm

1. $X \sim \mathrm{U}(0, 1)$
2. If $X <$ *sympathy*(k, r)
      Accept session
      If node is the last but one in r
        Send acknowledgment to s
      Else Forward request to the next node in r
   Else
      Reject session
      Send negative acknowledgment to s.

The PAY-IT-FORWARD Strategy. This strategy is motivated by the TIT-FOR-TAT policy in [9]. The TIT-FOR-TAT strategy was developed for the two player Iterated Prisoner's Dilemma game. By this strategy, at any given game, a player mimics the strategy followed by the opponent in the previous game. This was found to be a very good strategy. In our situation however, there are the following limitations: (i) it is a multiplayer game and (ii) a node does not have memory of whether it has been helped earlier by another player. Hence, the intuition here is that a node should do unto the other network components what it has done unto it.

According to the PAY-IT-FORWARD strategy, each node is associated with two parameters *credit* and *debit*. The parameter *credit* intuitively reflects the amount of 'help' that a node has received by other nodes relaying its messages. On the other hand, the parameter *debit* reflects the amount of 'help' that the node has rendered in relaying messages for other nodes. The PAY-IT-FORWARD algorithm attempts to balance the amount of credit and debit at each node. For a fixed value of *sympathy*, a node is more willing to accept a request if it has received more help than it has given. Conversely, if a node has been generous in the past without receiving a commensurate amount of assistance from other nodes, then it is inclined to reject relay requests. As the value of *sympathy* decreases, nodes tend to behave more selfishly.

In the following, u denotes the traffic session, while *credit*(k, r) and *debit*(k, r) represent the *credit* and *debit* of the k-th node on route r, $r \in \mathcal{R}(s, d)$, respectively.

Source Algorithm

1. Set $r = 1$
2. /* Loop over all routes available to the source */
   While $r \leq R_{max}$
      Send session request on route r
      If request is accepted on route r
        Break from while loop
      Else $r = r + 1$
   End While
3. If $r \leq R_{max}$
   /* Session accepted by route r */
      Transmit on route r
      $k = 2$
      While $k < N(r)$
      /* Update *debit* for relay nodes on route r */
        $\textit{debit}(k, r) = \textit{debit}(k, r) + \textit{file\_size}(u) \cdot [p_{tx}(k, r)/\textit{rate}(u)]$
        $k = k + 1$
      End While
      $\textit{credit}(1, r) = \textit{credit}(1, r) + \textit{file\_size}(u) \cdot [p_{tx}(1, r)/\textit{rate}(u)]$
      /* Update *credit* for the source */
   Else Session is blocked.

Relay Node Algorithm

1. If $\textit{credit}(k, r) > (1 - \textit{sympathy}(k, r)) \cdot \{\textit{debit}(k, r) + \textit{file\_size}(u) \cdot [p_{tx}(k, r)/\textit{rate}(u)]\}$
      Accept session
      If node is the last but one in r
        Send acknowledgment to s
      Else Forward request to the next node in r
   Else
      Reject session
      Send negative acknowledgment to s.

Note that, in the RANDOM strategy, each node arbitrarily decides on whether to relay traffic or not. On the other hand, in the PAY-IT-FORWARD strategy each node tries to repay its debt to the network.

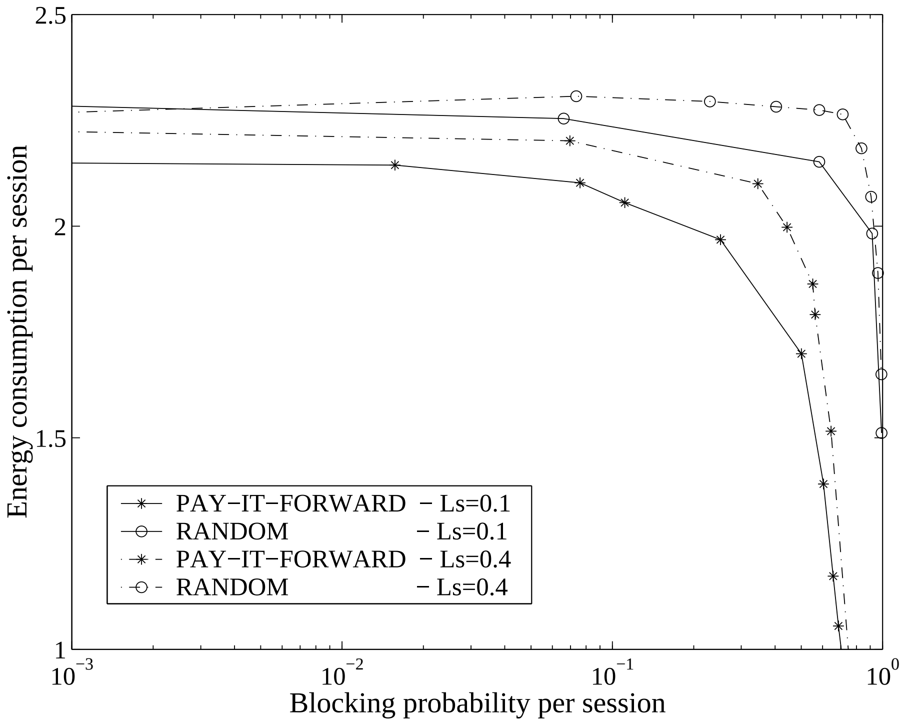

Figure 1: Average energy consumption per session vs. blocking probability for the two strategies RANDOM and PAY-IT-FORWARD, when *sympathy* is the same for all users and $L_s = 0.1, 0.4$.

Both the RANDOM and the PAY-IT-FORWARD strategy can be implemented in a distributed manner. Each node decides whether to accept or to refuse a connection based on its 'local' parameters, independently of other nodes. For the RANDOM strategy each node flips a coin independently to make its decision. In the PAY-IT-FORWARD strategy, a node's decision is based only on the value of *credit* and *debit*, on the source rate, on the file size and on the energy required to transmit to the next hop. Hence, the only non local information that a node needs is the rate and file size for the relay request.

4 Numerical Results

We derived results by using the software tool MATLAB. We simulated an ad hoc network composed of $N = 20$ stationary nodes. As already mentioned, the network nodes are uniformly distributed in circular region of unit radius. We consider a discrete time slotted system; in each time slot the number of sessions generated is assumed to be Poisson distributed with rate L_s. The average file size is equal to 1 Mbyte, while possible values of data rate are 1.0, 2.0, 5.5, and 11.0 Mbps, as in the 802.11 WLAN system. The maximum number of routes between each source-destination pair is equal to 2. We take as performance metrics the session blocking probability and the average energy consumed per session, which is defined as the total energy spent by a node to support both its own traffic and other nodes' sessions, divided by the number of sessions generated by the node, that have been accepted.

We first consider a scenario where all the nodes in the network use the same strategy and have the same behavior, i.e., the same value of *sympathy*, and compare the RANDOM and the PAY-IT-FORWARD policy. Figure 1 shows the average energy consumption and the session blocking probability as functions of the parameter *sympathy*. Curves are obtained for $L_s = 0.1$ and 0.4. For both the RANDOM and the PAY-IT-FORWARD policy, a lower energy consumption is achieved at the expense of a higher blocking probability. The desired trade-off between the two performance metrics can be obtained by selecting the proper value of *sympathy*. Also, for a given blocking probability, PAY-IT-FORWARD allows for smaller values of energy consumption than the RANDOM strategy.

Figures 3 and 3 present the average energy consumption per session and the session blocking probability, that are obtained when two classes of users, which apply the same strategy but with different value of *sympathy*, operate in the network. In particular, we consider a group of altruistic users with *sympathy* equal to 0.9 and a group of selfish users with *sympathy* equal to 0.5. This scenario may either model the case where user terminals have different energy constraints or the case where some users attempt to tweak their algorithm to maximize their own benefit. In the plots, the curves labeled by A and S represent the performance of altruistic and selfish users, respectively.

Results in Figure 3 show that as the number of selfish users grows, the blocking probability increases for both the classes of users because it is more likely that a route includes selfish nodes and, hence, that a session request is refused. Also, note that the performance of the RANDOM and the PAY-IT-FORWARD strategy are quite close and that for each policy the curves corresponding to the two classes of users overlap.

Figure 3 shows that, in this second scenario, the PAY-IT-FORWARD strategy still outperforms the RANDOM policy. Moreover, when the RANDOM policy is adopted, selfish users can obtain a lower energy consumption than altruistic users if their density in the network is less than 0.5, although the energy gain is negligible. Under the same conditions, when the PAY-IT-FORWARD strategy is applied, selfish users can achieve a significant reduction in energy consumption. This suggests that, by using the PAY-IT-FORWARD policy, the network is able to guarantee to selfish users a lower energy consumption, provided that their density is low and the obtained blocking probability is acceptable. If the number of selfish users exceeds a given threshold, these nodes will incur a higher energy consumption than altruistic nodes. Hence, the PAY-IT-FORWARD strategy is robust against users' attempt at tweaking their behavior, since users, that are supposed to be altruistic, will get poorer performance if they start behaving selfishly.

5 Conclusions and Future Work

We addressed the problem of resource sharing in an ad-hoc wireless network. In such a setting, it is not obvious that all the nodes will cooperate to achieve a global objective. Rather, some users may behave 'selfishly' due to their particular needs or to the physical limitations of their radio terminal. We considered as indices of the user's performance the average energy consumption per traffic session and the session blocking probability. We explored the trade-off that exists between these metrics when two simple strategies are applied: RANDOM and PAY-IT-FORWARD. We studied the case where all the users in the network use the same strategy and have the same behavior, and we found that the PAY-IT-FORWARD strategy outperforms the RANDOM policy. Then, we considered the scenario where some users are more selfish than others; this scenario models the case where either user terminals have different energy constraints or some users attempt to tweak their algorithm to maximize their own benefit. Results showed that selfish users tend to do well when their number is low; while, they get poor performance when their density increases.

We would like to emphasize that this work is a first attempt at studying the impact of user interaction and behavior on the performance of ad hoc networks. A great deal of work remains to be done. For example, the behavior of the user energy consumption and of the session blocking probability as the node density varies need to be further investigated. Also, the issues addressed in this paper should be studied in a systematic fashion by using the tools of non-cooperative game theory. In particular, the possible equilibrium states, that can be achieved by different users through selfish strategies, should be defined. This will provide useful insight into designing optimal policies for resource sharing in ad-hoc networks.

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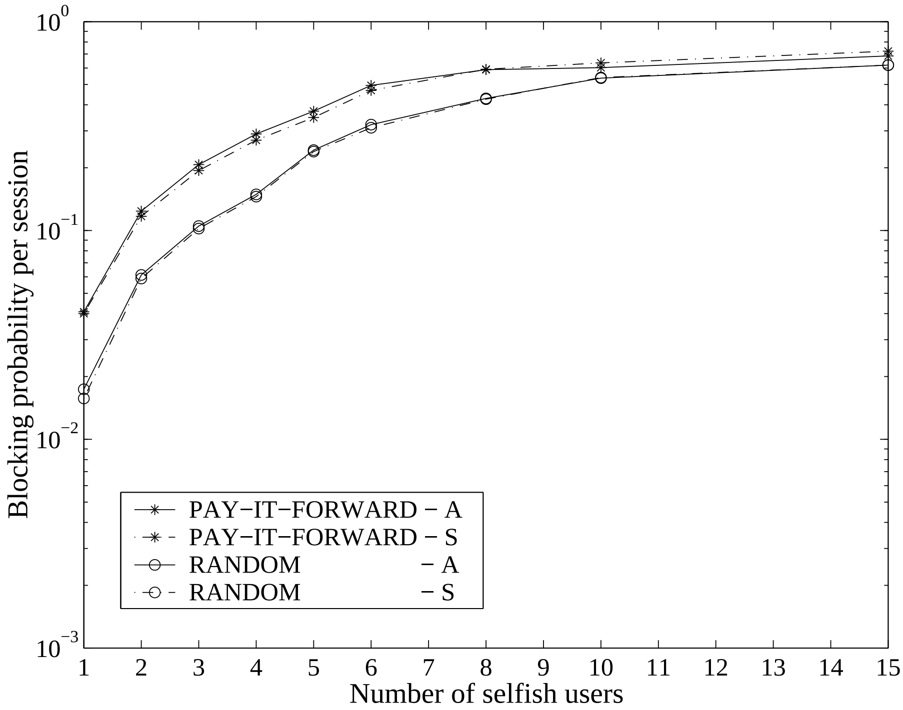

Figure 2: Blocking probability as a function of the number of selfish users in the network. The RANDOM and the PAY-IT-FORWARD strategy are compared for $L_s = 0.1$. A=Altruistic users; S=Selfish users.

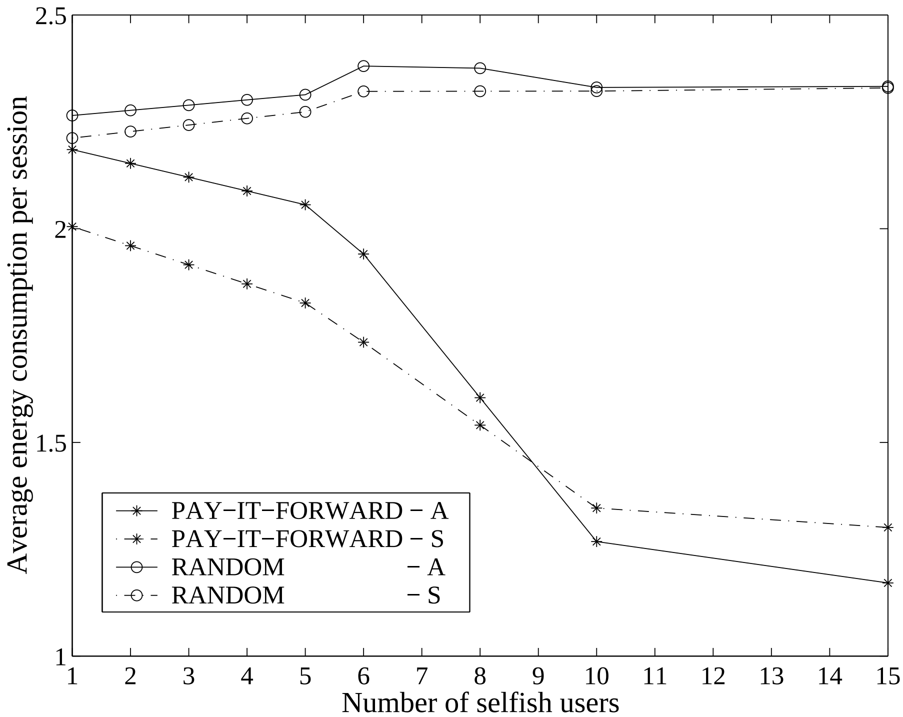

Figure 3: Energy consumption per session as a function of the number of selfish users in the network. The RANDOM and the PAY-IT-FORWARD strategy are compared for $L_s = 0.1$. A=Altruistic users; S=Selfish users.