

# Avoiding Throughput Bottlenecks for Energy Efficient Joint Power Control and Routing in Ad Hoc Wireless Networks

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*Abstract*—Tight energy constraints in wireless ad hoc networks require the use of efficient interference management techniques, such as power control and energy aware routing. Moreover, in such networks, there is a strong coupling between power allocation and route selection, which naturally leads towards joint optimization schemes. Joint power control and routing algorithms which minimize the total energy consumption in the network have been recently proposed in the literature. In this paper, we address the problem of joint design in the context of energy minimization, subject to throughput constraints. More specifically, it is considered that the reduction in network throughput is determined by the bottleneck nodes, which serve as relays for many traffic flows. Avoiding the formation of bottleneck nodes increases the network throughput and also increases the network lifetime, by avoiding the situation in which some nodes wear off faster than the others.

## I. INTRODUCTION

A mobile ad hoc network consists of a group of mobile nodes that spontaneously form temporary networks without the aid of a fixed infrastructure or centralized management. The communication routes between source-destination pairs are determined by the routing protocol, which finds the best possible paths between source and destination nodes, according to some specified cost criterion. With tight energy constraints in wireless ad hoc networks routing protocols using energy related cost criteria have been recently investigated in the literature (e.g. [1],[2]). Moreover, in such networks, there is a strong coupling between power allocation and route selection, which naturally leads towards joint optimization schemes. Joint power control and routing algorithms which minimize the total energy

consumption in the network have been recently proposed in the literature [3], [7]. In particular, the joint distributed power control and routing algorithm for Code Division Multiple Access (CDMA) ad hoc networks proposed in [3], uses the transmission power of the nodes as the cost metric for shortest-path routing algorithms, and iteratively and sequentially adjusts the power and route selection, until no further energy reduction can be obtained.

While it has been shown in [3] that the joint optimization results in orders of magnitude improvement in the energy consumption, the final network configuration may lead in some cases to the formation of bottleneck nodes (nodes that are relaying many traffic flows), which may yield reduced network throughput.

In this paper, we address the problem of joint power control and routing design in the context of energy minimization and subject to throughput constraints. More specifically, we try to avoid the formation of bottleneck nodes by introducing two new routing metrics.

In a multi-hop ad hoc network, the limiting throughput per network is given by the node relaying the most traffic. A general definition of this throughput can be given as:  $\lambda/n$ , where  $\lambda$  is the throughput capability of a node given by the system model,  $n$  denotes the number of flows relayed by a node. Obviously, the greater the number  $n$  is, the more reduction the throughput suffers. The throughput bottleneck will occur at nodes that have the maximum number of relayed flows ( $n_{max}$  = maximum  $n$  over the network). Both routing metrics that we propose in this paper, aim to reduce  $n_{max}$ .

The first metric, dynamic weighted power metric routing (DWP), applies dynamic weighting on the power aware routing metric of a link every time it is selected. The proposed dynamic metric sequentially penalizes those nodes that have been used as relaying before, hence avoid the creation of nodes with many relaying flows.

The second metric, adaptive load aware power metric routing (ALAP), introduces the traffic load information into the power aware routing metric. Current traffic load information is considered as a predictor for possible bottleneck nodes in the next iteration. According to the bottleneck predictor, heavier costs are assigned to the possible bottleneck nodes. Thus, they have less chance to be selected by routing at the next step, and are unlikely to become bottleneck nodes.

Our simulation results show that implementation of the joint power control-routing algorithm with these two new metrics, results in higher throughput than the algorithm presented in [3], at the expense of a slightly increased energy per bit consumption. Comparing the two proposed metrics, we find that DMP gives better performance than ALAP in throughput, while ALAP is more energy efficient.

The rest of this paper is organized as follows. In Section II, we present the system model on which our analysis is based. Section III describes the energy efficient joint power control and routing algorithm with and without throughput constraints. Finally, simulation results are presented in section IV, followed by conclusions in section V.

## II. SYSTEM MODEL

We consider an ad hoc network consisting of  $N$  mobile nodes. For simulation purpose, the nodes are assumed to have a uniform stationary distribution over a square area, of dimension  $D^* \times D^*$ , but this is not a necessary assumption for the analysis. The multi-access scheme is synchronous direct-sequence CDMA (DS-CDMA) and all nodes use independent, randomly generated and normalized spreading sequences of length  $L$ . The transmitted bits are detected using a matched filter receiver. Each terminal  $j$  has a transmission power  $P_j$  which will be iteratively and distributively adapted according to the current network configuration. The traffic can be relayed through intermediate nodes. It is assumed that each node generates traffic to be

transmitted towards a randomly chosen destination node. If traffic is relayed by a particular node, the transmissions for different sessions at that node are time multiplexed.

We define the link Quality of Service (QoS) measure for one terminal (say  $j$ ) to be the energy consumed for the correct transmission of an information bit,  $E_b^j$  [3], [8]:

$$E_b^j = \frac{MP_j}{mRP_c(\gamma)}, \quad (1)$$

By minimization of (1), we can get the optimal target SIR,  $\gamma^*$ . Therefore, a link has maximal utility, and operates at minimal energy-per-bit, if the SIR achieved on that particular link is  $\gamma^*$ .

For the numerical results, we have considered a system employing non-coherent frequency-shift-keying (FSK) modulation, for which the BER is given by

$$BER = \frac{1}{2}e^{-\frac{\gamma}{2}}. \quad (2)$$

## III. ENERGY EFFICIENT JOINT POWER CONTROL AND ROUTING

In the previous section we showed that to obtain minimum energy-per-bit consumption for a transmission on a given link, a target SIR requirement of  $\gamma^*$  should be imposed. The achievable link SIR depends on the transmission powers for all nodes.

Since it can be shown that  $\gamma^*$  is a global minimum of the energy function, if  $SIR \neq \gamma^*$  the system overspends energy for the transmission. Specifically, if  $SIR < \gamma^*$  many retransmissions are required which also affects the throughput and the transmission delay of the link. On the other hand, if  $SIR > \gamma^*$ , the surplus gain achieved by a better SIR is overcome by a high required transmission power. Taking into account the above considerations we express the link QoS requirement for an arbitrary link  $(i, j)$ ,  $i, j = 1, 2, \dots, N$  as

$$SIR_{(i,j)} \geq \gamma^*, \forall (i, j) \in S_a^r, \quad (3)$$

where  $S_a^r$  is the set of active links for the current routing configuration  $r$ , obtained using the routing protocol. The joint optimization problem at the

network level can then be formulated as

$$\begin{aligned}
& \text{minimize } \sum_{i=1}^N P_i \\
& \text{subject to} \\
& \quad SIR_{(i,j)} \geq \gamma^*, \forall (i,j) \in S_a^r \quad (4) \\
& \quad P_i \geq 0 \\
& \quad \text{and } r \in \Upsilon,
\end{aligned}$$

where  $\Upsilon$  is the set of all possible routes. From (4) we can see that optimal power allocation depends on the current route selection. On the other hand, for a given power allocation, efficient routing may reduce the interference, thus further decreasing the required energy-per-bit.

### A. Power Control Issues

To reduce the implementation complexity, it is assumed that the power control adjusts the power level of the mobile node, such that the transmitted power of that node is common for all active links that have that node as a source node. Consequently, if multiple active transmission links start at node  $i$ , then the worst outgoing link must meet the target SIR with equality. If we denote the set of all outgoing links from node  $i$  as  $S_i^*$ , the minimal power transmission conditions become

$$\min_{k \in S_i^*} SIR_k = \gamma^*, \forall i = 1, 2, \dots, N. \quad (5)$$

We now express the achievable SIR for an arbitrary active link  $(i, j) \in S_a^r$ :

$$SIR_{(i,j)} = \frac{h_{(i,j)} P_i}{\frac{1}{L} \sum_{k=1, k \neq i, k \neq j}^N h_{(i,j)} P_k + \sigma^2}, \quad (6)$$

where  $h_{(i,j)}$  is the link gain for link  $(i, j)$ , and  $\sigma^2$  is the background noise power.

From (5) and (6), the powers can be selected as

$$\begin{aligned}
P_i &= \max_{(i,j) \in S_i^*} \frac{\gamma^*}{h_{(i,j)}} \left[ \frac{1}{L} \sum_{k=1, k \neq i, k \neq j}^N h_{(k,j)} P_k + \sigma^2 \right] \\
&= \max_{(i,j)} I_{(i,j)}(\mathbf{p}), \quad (7)
\end{aligned}$$

where  $\mathbf{p}^T = [P_1, P_2, \dots, P_N]$ .

It can be proved that  $T(\mathbf{p}) = \max_{(i,j)} I_{(i,j)}(\mathbf{p})$  is a standard interference function [9]. Hence, for a feasible system, an iterative power control algorithm can be implemented as

$$P_i(n+1) = T(\mathbf{p}(n)), \forall i = 1, 2, \dots, N, \quad (8)$$

and it is shown to be convergent to a minimal power solution [9], for both synchronous and asynchronous power updates.

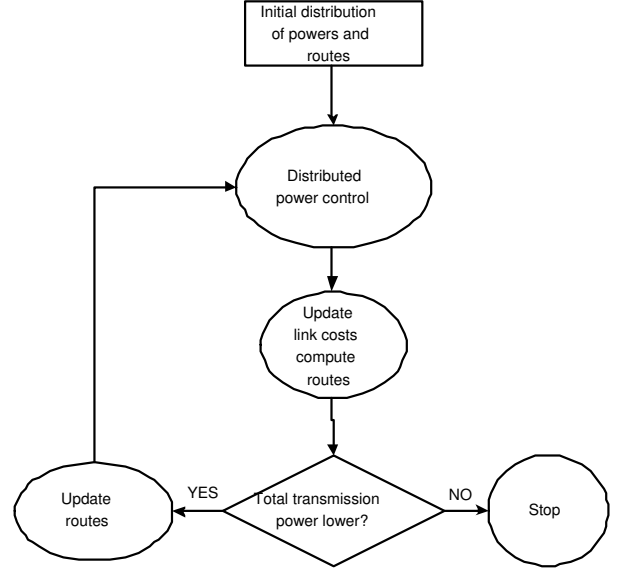


Fig. 1. Joint power control and routing.

### B. Joint Power Control and Routing

Starting from an initial distribution of powers and routes, and assuming that the system is feasible for the initial configuration, the integrated power control and routing algorithm is summarized in Figure 1.

For a given network topology distributed power control is implemented, which ensures that the smallest SIR of all the outgoing active links from one node is greater or equal to the target SIR,  $\gamma^*$ . The routes are then updated based on the link costs defined below, followed by a new iteration of power control. The power control and routing iterations form a close loop, which stops when there is no more improvement in total transmission power. Our contribution in this paper consists on the introduction of throughput constraints in the routing, by means of two new routing metrics.

In order to estimate costs for links that are not currently active, the achievable SIR for all links must be estimated. We note that for a given distribution of nodes in the network, the achievable SIR depends only on the nodes' transmitted powers and is independent of the current route assignment. Hence, the estimated SIR for link  $(i, j)$  ( $SIR$ ) can be calculated with the information of the link gains  $h_{(i,j)}$ , the transmitted powers of all nodes,  $P_j, j = 1, 2, \dots, N$  and the extended estimated interference at all the other nodes.

1) *Power Metric Routing*:: The routing scheme proposed in [3] uses Dijkstra's algorithm [4] with associated costs for the links. The cost for an arbitrary link  $(i, j)$  is determined as

$$c(i, j) = \begin{cases} P_i & \text{if } SIR_{(i,j)} \geq \gamma^* \\ \infty & \text{if } SIR_{(i,j)} < \gamma^* \end{cases} \quad (9)$$

Using (9), the resulting routes yield minimal energy per information bit for a given power allocation across the nodes.

The drawback for using this routing metric might be that nodes that are in "good positions" (have a low transmission power) will be used by many traffic flows as relaying nodes and will become throughput bottleneck nodes for the whole network. To overcome this problem, we propose two new routing metrics to be used for the joint power control and routing algorithm. These new metrics are described in detail in the following subsections.

2) *Dynamic Weighted Power Metric Routing (DWP)*: In DWP, we replace the routing scheme in [3], with one that dynamically adjusts the link costs, taking into account the relaying load of each node. The algorithm is summarized as follows:

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initial cost  $c(i, j)$  as in (9);
for i=1:N
  Dijkstra's routing algorithm for node i;
  for j=1:N
    if node(j) is in route i;
       $P_j \leftarrow W \times P_j$ ;
    end
  end
  update cost  $c(i, j)$ ;
end

```

$W$  is the weighting parameter, which controls the tradeoff between the power/energy savings and the overall network throughput. For  $W = 1$ , this algorithm becomes identical to the one proposed in [3]. DWP sequentially penalizes those nodes that have been used as relaying nodes before, hence avoiding the creation of nodes with many relaying flows.

3) *Adaptive Load Aware Power Metric Routing (ALAP)*: As an alternate solution, we also propose ALAP which avoids adding too much traffic load

to a node with a relatively higher current load level. The main idea of ALAP is to introduce the traffic load information into the power aware routing metric. Starting from an initial routing assignment, current traffic load information determined by the routing can be considered as a predictor for possible bottleneck nodes in the next iteration. The routing metrics of all the links are updated for the next routing according to the bottleneck predictor. Heavier costs will be assigned to the links which have possible bottleneck nodes as transmitting nodes. Thus, the possibility for these links to be selected in the next routing iteration will be reduced.

The cost for an arbitrary link  $(i, j)$  is determined as

$$c(i, j) = \begin{cases} \alpha_i K_i P_i & \text{if } SIR_{(i,j)} \geq \gamma^* \\ \infty & \text{if } SIR_{(i,j)} < \gamma^*, \end{cases} \quad (10)$$

where  $P_i$  is the transmission power of node  $i$ ,  $K_i$  is the number of outgoing links of node  $i$ ,  $\alpha_i$  is the bottleneck node co-efficient:

$$\begin{cases} \alpha_i = 1 & \text{if } K_i \neq K_{max} \\ \alpha_i > 1 & \text{if } K_i = K_{max}, \end{cases} \quad (11)$$

where  $K_{max} = \text{MAX} \{K_j ; \text{for } j = 1 \dots N\}$ , and  $K_i = K_{max}$  means node  $i$  is a bottleneck node.

Using this routing metric, the integrated power control and routing algorithm can be summarized as follows:

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Given initial routing assignment  $S$ ;
1: Power control;
2: Compute traffic load  $\{K_i\}$  according to  $S$ ;
3: Update routing cost  $c(i, j)$  for all the links according to (3)(4);
4: Dijkstra's routing algorithm update  $S$ ;
5: IF total transmission power has been reduced
  Go To Step 1;
ELSE
  Stop;
END

```

It can be seen that  $c(i, j)$ , the cost of link  $(i, j)$ , will be adjusted according to the value of  $K_i$ , the traffic load of node  $i$ . When  $K_i$  increases, the cost of link  $(i, j)$  increases as well. The more  $K_i$  increases, the more the cost will go up.

Furthermore, the increment of cost can also be adjusted by  $\alpha_i$ , the bottleneck node coefficient. If  $K_i = K_{max}$ , node  $i$  is a bottleneck node and  $\alpha_i$  will be greater than 1. Thus, the increment of cost is much greater for the bottleneck nodes, compared to the other nodes, for which  $\alpha_i$  equal to 1. Consequently, the bottleneck node becomes the first node that should be avoided for new route updates.

#### IV. SIMULATIONS

In this section, we present some numerical examples for an ad hoc network with 25, 35, 45 and 55 nodes, respectively, uniformly distributed over a square area of  $200 \times 200$  meters. The target SIR  $\gamma^*$  is selected to be 12.5, and the noise power  $\sigma^2$  is  $10^{-13}$ , which approximately corresponds to the thermal noise power for a bandwidth of 1 MHz. We consider low rate data users, using a spreading gain of  $L = 128$ . For this particular example, we choose equal initial transmit powers, 70dB above the noise floor. The weighting parameter  $W$  for DMP metric routing is set to 2, and bottleneck coefficient  $\alpha$  for the ALAP metric routing is set to 10.

Figure 2 depicts the throughput supported by network versus the number of nodes (N). Each curve of this plot is the average throughput obtained from different random initial nodes distributions. The throughput is defined as  $\lambda/n$ , where  $n =$  number of flows that are using the limiting node relaying the most traffic, and  $\lambda = R/M, R = 10^4 \text{bits/sec}$ ,  $M = 80 \text{bits}$ ,  $M$  is packet length. It can be noticed from this plot that the two new proposed algorithm give higher throughput than the original algorithm. Moreover, DMP gives better performance than ALAP in throughput, while from Figure 3 we see that ALAP provides better energy efficiency.

In particular, Figures 4 and 5 illustrate the total transmission power and energy per bit, respectively, for a network of 55 nodes. In Figure 4, it can be seen that the total transmitted power in the network progressively decrease as the proposed algorithm iteratively refines power and routes. The values in Figure 4 represent the total transmitted power obtained over a sequence of iterations; [power control, routing, power control, routing, power control]. It can be further noticed that DMP metric based routing in this case has a slightly higher total transmitted power than both the original and the ALAP

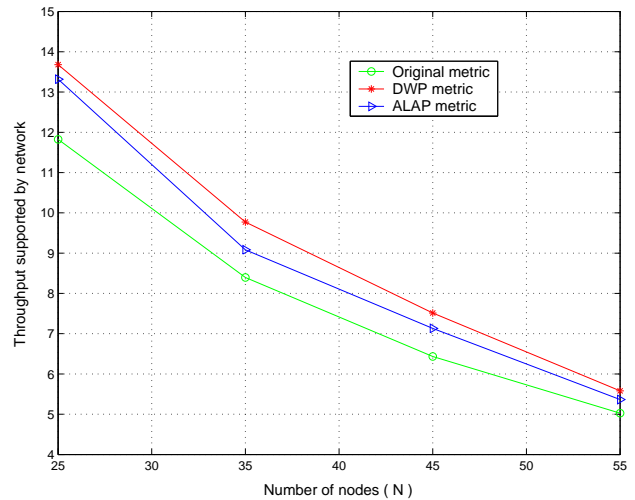


Fig. 2. Throughput supported by network versus Number of nodes.

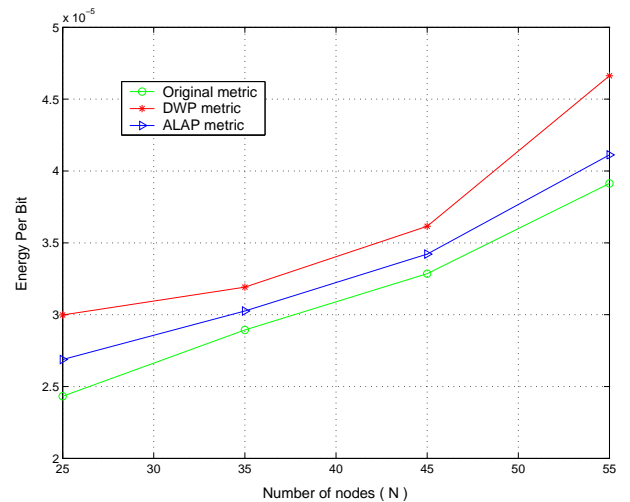


Fig. 3. Energy per bit consumption versus Number of nodes.

scheme. In Figure 5, the achieved energy-per-bit is compared for the same experiment with the first energy value, which represents the energy-per-bit obtained in the initial state (this is obtained for equal powers, with the routes selected to minimize the energy per bit consumption). It can be seen that substantial improvements are achieved. Further, we also notice that DMP metric based routing here has a higher final energy than the other two metrics.

We can see that there is a trade-off between the throughput and the energy consumption. To improve the throughput, we need to distribute the traffic load uniformly across all nodes, which means that sometimes, we may have to give up the links with the minimum transmission power to favor a more uniform load across the network.

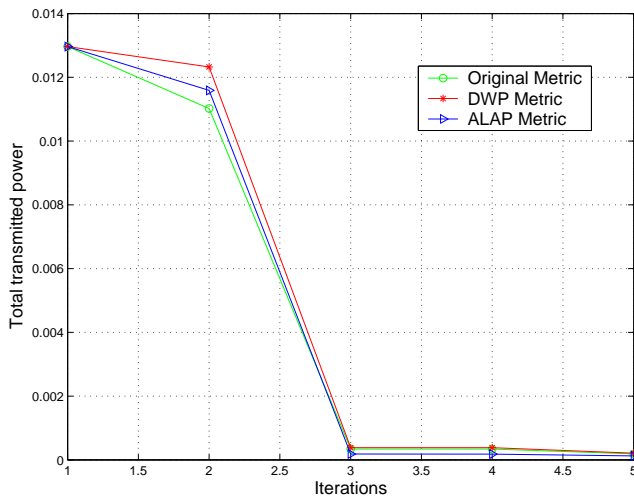


Fig. 4. Total transmission power.

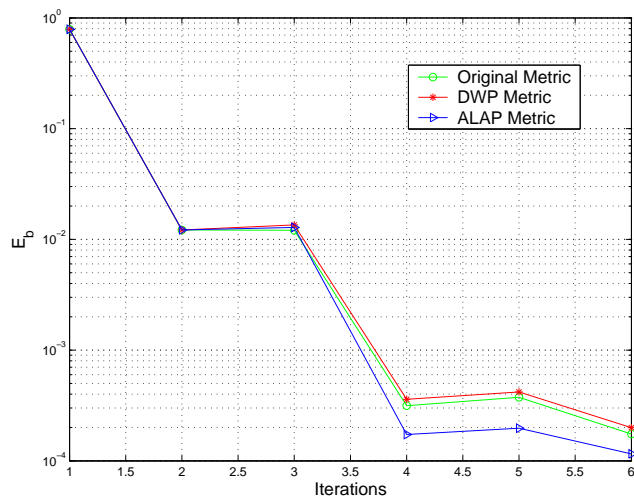


Fig. 5. Energy per bit.

For the DMP metric, the weight applied on the power aware routing metric of each node increases exponentially as the the number of traffic flows relayed by the node grows up. It gives a better performance on avoiding bottlenecks but leave less options for the joint optimization of power control and routing. As a consequence, a DMP willyield a higher energy consumption. On the other hand, for ALAP metric, the cost of a link increases linearly as the current traffic load climbs up, and it thus provides more options to obtain a compromise between the throughput and the energy consumption.

Furthermore, it is worth mentioning that the network lifetime can also be improved by using the proposed metrics. Compared to other nodes, bottleneck nodes will consume a lot more energy

for the relaying traffic. The battery of the bottleneck node will drain much faster than that of the other nodes, and this will accelerate the collapse of the whole network [10]. The proposed new metrics help to avoid overusing of specific nodes, and will therefore prolong the time before the first node dies (power down) in the ad hoc network, which will improve the time before the network becomes partitioned. This is also crucial requirement for the practical applications of ad hoc networks.

## V. CONCLUSIONS

In this paper, we have proposed two new routing metrics for joint power control and routing, which lead to significant improvement in the system throughput compared to results from earlier work [3]. These new metrics address routing in the context of energy minimization, and subject to throughput constraints. Using the proposed schemes, the formation of bottleneck nodes is avoided, with immediate positive consequences on the network throughput and on the network lifetime.

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