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MULTICOST ROUTING IN WIRELESS AD-HOC NETWORKS WITH VARIABLE TRANSMISSION POWER

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ABSTRACT

In this work we study the combination of multicost routing and variable transmission power in wireless ad-hoc networks. In multicost routing, each link is assigned a cost vector consisting of several parameters. These parameters are treated separately and are combined at the end of the algorithm using various optimization functions, corresponding to different routing schemes, for selecting the optimal path. The cost parameters we use are the hop count, the interference caused, the node residual energies, and the node transmission powers. We assume that nodes can use power control to adjust their transmission power to the desired level. The experiments conducted show that the combination of multicost routing and adjustable transmission power can lead to reduced interference and energy consumption, improving network performance and lifetime.

I. INTRODUCTION

An ad-hoc network is a set of nodes that have the ability to communicate wirelessly without the existence of any fixed infrastructure. Nodes in an ad-hoc network use other nodes as intermediate relays to transmit packets to their destinations. Since nodes are usually battery operated, energy conservation is an important issue. Furthermore, because of the broadcast nature of the wireless medium, ad-hoc networks are also limited by interference/capacity considerations.

The combination of power control and multicost routing can help alleviate the energy and interference limitations of ad-hoc networks. We propose and evaluate joint power control and multicost routing algorithms that incorporate the following cost parameters: the hop count, the interference caused by a packet transmission, the residual energy of the nodes, and the transmission power used. We assume that nodes can adjust their transmission power to the minimum required level for coherent reception at the recipient node; in contrast, networks that use static transmission power consume more power than necessary, leading to energy squander and increased interference. Furthermore, multicost routing makes application-specific routing possible, and permits the use of metrics that could not be considered in single-cost routing.

The context in which our energy- and interference-aware routing schemes are evaluated is that of the evacuation problem, where the network starts with a certain number of packets to be routed and a certain amount of energy per node, and the objective is to serve the packets with minimum delay, or to serve as many packets as possible before the energy at the nodes is depleted. We are interested in the mean and the variance of the residual energy at the nodes after all data transfer has been completed, the average number of hops on the paths taken, the fraction of packets delivered to their destination, the average packet delay, and the network throughput. Our simulation results show that the proposed multicost routing algorithms reduce interference and energy consumption, spread energy consumption evenly across the network, and improve network performance and lifetime.

The remainder of the paper is organized as follows. In Section 2 we report previous work. In Section 3 we describe the proposed multicost interference/energy-aware routing algorithms. In Section 4 we present the simulation model. In Section 5 we present the performance results obtained. Finally, in Section 6 we conclude the paper.

II. PREVIOUS WORK

A great deal of previous work on ad-hoc networks has focused on the design of efficient routing protocols, where efficiency is interpreted using a variety of performance criteria. Some works have designed routing protocols that exhibit small end-to-end delay, adaptiveness to the movement of the nodes, efficient use of the bandwidth, small number of packet transmissions, or optimize some other criterion. All these algorithms are single-cost, in the sense that for each link there is a scalar cost parameter. In the present work, we focus on multicost routing, where a vector of cost parameters characterizes each link.

[1][2][3] present some well known routing algorithms for ad-hoc networks, where the metric optimized is the hop count or the end-to-end delay. [4] uses the link quality as the cost metric for routing, while [17] uses the ETX metric, which incorporates the link loss ratios, and the interference among successive links of a path. A great deal of work has also been performed on energy efficient routing. [6] is one of the first works proposing energy aware routing for ad-hoc networks. In [5] a distributed protocol to find the minimum power topology is presented. In [6] five energy-related metrics are presented. In [7] and [8] link costs are calculated based on the energy expenditure for unit flow transmission and the initial and residual energy at the transmitting nodes. In [9] a cost metric that is a function of the remaining battery level and the number of neighbors of a node is used. Transmission power control is also proposed in various works to achieve efficient energy use. In [10] two algorithms are proposed for the calculation of the node transmission power. In [7] a distributed algorithm is presented that maximizes the node lifetimes. Other works incorporate power control in the MAC layer [11]. In [12] the Slow Start

MAC Protocol is proposed, where power control and a slow start mechanism is used for the transmission of RTS/CTS and DATA packets.

All the protocols mentioned above base their decisions on a single, scalar metric (which may be a function of several metrics). Despite the potential of multicost routing, the research activity in this field has not been intense. The idea of multicost routing was presented in [15], where it was applied to wireline max-min fair share networks. [16] has investigated multicost routing in wireless ad-hoc networks, but this work does not take interference metrics into account and it does not assume a power control capability.

III. INTERFERENCE/ENERGY-AWARE MULTICOST ROUTING ALGORITHMS

A. *The Multicost Routing Approach*

In single-cost routing, each link is assigned a single cost measure (that may even be a function of several parameters), and a minimum-cost algorithm is used to find the optimal path. In contrast, in the multicost routing approach considered in the present paper, each link is characterised by a vector of cost parameters. A cost vector is then defined for each path based on the cost vectors of its constituent links. During the path discovery process, paths found to be dominated by another path with respect to all cost components, are discarded and ignored thereafter. Finally, an optimization function is applied to the cost vectors of the paths in order to select the optimal path. The multi-cost problem is a generalization of the multi-constraint problem, where no constraints exist.

The basic difference between multicost and single-cost routing is that in multicost routing the cost parameters are treated separately until the very end, when an optimization function is applied, while in single-cost routing all the parameters of a link are combined in a single metric. Due to this feature single-cost routing restricts the type of criteria that can be used for routing, and cannot provide different QoS levels. Moreover, multicost routing maintains a set of (non-dominated) paths for each source-destination pair, instead of just one path, which is the case for single-cost algorithms. Finally, the inclusion property (that is valid for the paths produced by single-cost routing) is not valid for the paths selected by multicost routing, indicating that the two approaches are very different.

Briefly summarizing the above, each link l is assigned a k-dimensional cost vector $u_l = (u_{1l}, u_{2l}, \dots, u_{kl})$. The cost vector $V(P) = (V_1, V_2, \dots, V_k)$ of a path P, is then obtained from the cost vectors of the links $l = 1, 2, \dots, j$, that comprise it by applying component-wise a monotonic associative operator $\otimes$ to each cost vector parameter:

$$V_i = \otimes_{l=1,\dots,j} u_{il}.$$

The operator may be different for different cost components. Generally, the parameters included in the path cost vector, are categorized by the way they are obtained from the link cost components, that is by the associative operator used for each component, and by the criterion that is applied (maximization or minimization) to select the optimal path.

B. *Cost Parameters for Ad Hoc Networks*

The cost parameters used in the proposed interference/energy-aware multicost routing algorithms are the following.

- The number of hops h. The associative operator $\otimes$ used in this case is the addition:

  $$h = \textstyle\sum_{l=1}^{j} h_l,$$

  where $h_l = 1$ for all links l. Paths with a small number of hops are generally preferable to longer paths.

- The minimum residual energy R of a path. Here we use the residual energy R_l at the transmitting node of link l as the link cost metric. The minimum residual energy on the path is then obtained by applying the minimization operator to the link cost metrics to obtain:

  $$R = min_{l=1,\dots,j} R_l.$$

  The minimum residual energy R indicates the degree to which a path is energy-critical. Paths with large minimum residual energy are generally preferable.

- The sum T_1, or the maximum T_∞ of the transmission powers used by the nodes on a path. If we denote by T_l the transmission power required for correct reception over link l, then T_1 is obtained by combining the link metrics using the additive operator, while T_∞ is obtained by combining the link metrics using the maximization operator:

  $$T_1 = \textstyle\sum_{l=1}^{j} T_l$$
  or
  $$T_\infty = max_{l=1,\dots,j} T_l.$$

  Paths with small values for T_1 consume little total energy, and are therefore preferable. Similarly, paths with small values of T_∞ avoid energy-critical nodes and are also preferable.

- The total interference I_1, or the maximum interference I_∞ caused by using a path. As in [13], we define the interference I_l caused by using link l as the number of nodes (other than the transmitter and the receiver) that are within the transmission range of the end nodes of link l. If we denote the distance between the transmitter a and the receiver b of link $l = (a, b)$ by $|a, b|$, then:

  $$I_l = I_{(a,b)} = |\{c \in V, |b, c| \leq |a, b| \cup |a, c| \leq |a, b|\}| - 2$$

  The total interference I_1 or the maximum interference I_∞ caused by using a path is obtained by employing the additive or the maximization operator, respectively, for combining the interference metrics of the links on the path:

  $$I_1 = \textstyle\sum_{l=1}^{j} I_l$$
  or
  $$I_\infty = max_{l=1,\dots,j} I_l$$

  Paths that create little total interference I_1 or little maximum interference I_∞ are generally preferable.

C. *The Multicost Routing Algorithms*

We combine the aforementioned cost parameters in different ways to produce various multicost routing algorithms. They following table contains the optimization functions examined. All of them select the path P with the minimum cost returned from the corresponding function.

Table 1: The multicost routing algorithms

Name	Optimization function
Minimum Interf.	$I_1(P)$
MAX Interf.	$I_\infty(P)$
Minimum Transmission Power	$T_1(P)$
SUM/MIN Energy-Interf.	$\frac{T_1(P)\cdot I_1(P)}{R(P)}$,
SUM/MIN Energy-Interf. -Half Hop	$\frac{\sqrt{h(P)}\cdot T_1(P)\cdot I_1(P)}{R(P)}$
MAX/MIN Energy-Half-Interf.	$\frac{T_\infty(P)*\sqrt{I_\infty(P)}}{R(P)}$
MAX/MIN Energy-Half-Interf. -Half Hop	$\frac{\sqrt{h(P)}*T_\infty(P)*\sqrt{I_\infty(P)}}{R(P)}$

The cost parameters h, T_1 and I_1 are additive metrics, while the R, T_∞ and I_∞ are concave. Based on [18] the complexity of any optimization function using at least two additive metrics is exponential, except in the case where one of the two is the hop metric. Also when one additive and one concave metric is used then the complexity of the corresponding optimization function is polynomial. As a result the SUM/MIN algorithms are exponential, while all the other algorithms are polynomial.

IV. SIMULATION MODEL

We implemented the multicost interference/energy-aware algorithms that correspond to the optimization functions of Table I, and carried out experiments using the Network Simulator[19]. The power of the signal at a receiver that is at distance d from a transmitter is taken to be:

$$P_r(d) = \frac{P_t*\lambda^2}{(4\pi)^2*d^a},$$

where P_t is the transmission power and λ is the wavelength used. The parameter a is the path loss constant, and is typically between 2 and 4 depending on the wireless channel. In our experiments we used $a = 2$, corresponding to the Free Space propagation model without multipath phenomena. Nodes are capable of adjusting their transmission power P_t. Specifically, we assume that all nodes can communicate directly with each other and hence the network is fully connected, but, depending on the routing algorithm employed, a node may choose not to use the direct link to the destination, and use a multihop path instead. We assume nodes know the physical distances in the network, and adjust their transmission power to the minimum value needed for coherent reception. Alternatively, a protocol such as the Slow Start power control protocol of [12] can be used, to enable the transmitter and the receiver to agree on the transmission power to be used. The MAC protocol we used is a modified version of IEEE 802.11. The ad-hoc network simulated consists of 16 stationary nodes randomly placed in a two-dimensional 350x350m^2 area. A constant (independent of the distance) energy is also consumed for packet reception. When a node is idle we assume that it consumes no energy.

In addition to the above adjustable power case, we also considered the static transmission power case; in that case, a node may expend an unnecessarily large amount of energy and cause unwarranted interference to other nodes, when the desired recipient is at a smaller distance than the static transmission range used. Since our emphasis is on comparing different multicost strategies, we assumed that nodes have all the information they need for making routing decisions (e.g., residual energy, transmission power), and no control/update packets and related overhead were included in our simulations. All algorithms under evaluation are equally affected by this decision, thus the comparison results are fair.

The performance of the proposed routing algorithms was evaluated in the setting of the evacuation problem. In this problem, there is a fixed number of packets per node (viewed as the traffic load of the network) that have to be delivered to their destinations ("‘evacuated" from the network). Packet destinations are uniformly distributed over all remaining nodes. Packet sizes are fixed to 500 bytes, and the transmission rate is equal to 0.1 packets/sec. The threshold for the received power required for correct reception is the same for all nodes.

V. PERFORMANCE RESULTS

We conducted experiments to evaluate the performance of the proposed interference/energy-aware multicost routing algorithms. The performance measures of interest were:

- The average residual energy E remaining at the nodes, when all packets have been evacuated from the network.
- The variance σ_E^2 of the node residual energies.
- The average number of hops h on the paths followed.
- The received-to-sent packets ratio, denoted by RS. Packets are dropped when a node runs out of energy before transmitting all the packets it was supposed to forward.
- The average packet delay D, defined as the average time that elapses between the beginning of an evacuation instance and the time a packet reaches its destination, averaged over all packets delivered to their destinations.
- The network throughput T, defined as the amount of information (in bytes) sent by the nodes during an evacuation interval, over the corresponding time duration.

Figures 1 and 2 illustrate the average residual energy at the end of an evacuation period, and the variance of the residual energies, respectively, as a function of the number of packets evacuated per node. The Minimum Transmission Power algorithm outperforms the other algorithms examined with respect to the average residual energy left at the nodes, while the Minimum Interference algorithm exhibits the worst performance. The results for the other algorithms lie between these two cases.

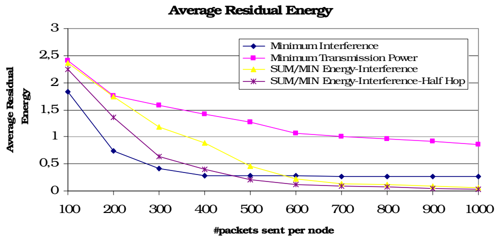

Figure 1: Average residual energy at the end of the evacuation problem, versus the number of packets evacuated per node.

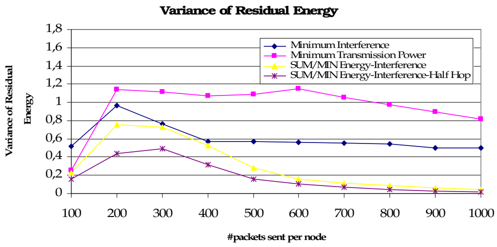

Figure 2: Variance of the residual energy at the end of the evacuation problem, versus number of packets evacuated per node.

Regarding the variance of the residual energy, shown in Figure 2, for almost all the algorithms examined the variance initially increases, but then starts decreasing rapidly as the number of packets that are evacuated increases. The algorithms that incorporate the path residual energy *R* in their cost functions (that is, the Mixed and Energy-Interference algorithms) perform better, achieving a more even distribution of energy consumption across the network. In contrast, the Minimum Interference and the Minimum Transmission Power algorithms do not change their paths when nodes start running out of energy, resulting in earlier depletion of the energy at some nodes, while there are still nodes with significant energy reserves.

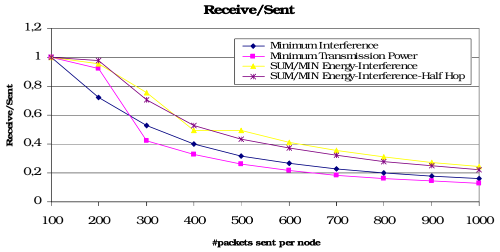

Figure 3: Received to sent ratio at the end of an evacuation problem, versus the number of packets evacuated per node.

Figure 3 illustrates the received-to-sent packets ratio *RS* as a function of the number of packets that are evacuated. The Energy-Interference and Mixed algorithms achieve better *RS* ratios, since they achieve in a longer lifetime for the network.

Regarding the average number of hops per path illustrated in Figure 4), the Minimum Transmission Power algorithm uses paths that have the largest number of hops. The paths selected by the Mixed algorithms consist of fewer hops than those selected by the Energy-Interference algorithms. A rather counter-intuitive observation is that the number of hops on the paths decrease when the number of packets evacuated increases. This is explained by considering the depletion of the energy at some nodes as more packets are evacuated, which results in the selection of paths with fewer but "longer" links.

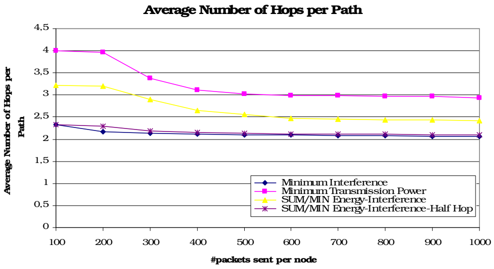

Figure 4: Average number of hops on the paths taken as a function of the number of packets evacuated per node.

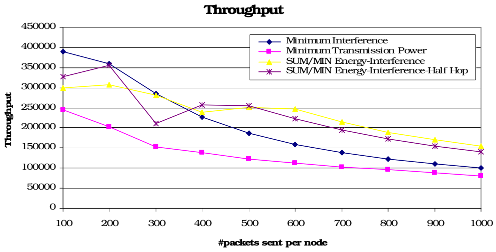

Figure 5: Average throughput over an evacuation period.

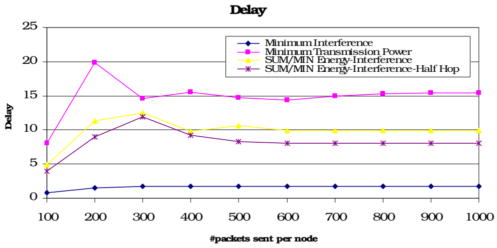

Figure 6: Average packet delay over an evacuation period.

Figures 5 and 6 illustrate the average throughput achieved during an evacuation period, and the average packet delay, respectively, versus the number of packets evacuated. The Mixed and the Energy-Interference algorithms achieve better throughput than the Minimum Interference algorithm, since the former algorithms energy efficient, and thus manage to deliver more packets to their destinations before the energy is depleted.

A. *Performance of max/min algorithms*

In this subsection we present the performance results for the MAX/MIN algorithms, obtained using the same network and parameters as above. Indicatively, we present the figures concerning the variance of the residual energy and the received-to-sent packets ratio. In Figure 7 we compare the MAX/MIN Energy-Half-Interference and the MAX/MIN

Energy-Half-Interference-Half Hop algorithms with the corresponding SUM/MIN algorithms. We observe that in all occasions the SUM/MIN algorithms performed better than the corresponding MAX/MIN algorithms. In other words, the T_1 and I_1 metrics, are more appropriate than the T_∞ and I_∞ metrics, respectively, in making routing decisions: the summing up the values of the transmission powers of the nodes on a path and the interferences on this path seems to be a more representative metric of the cost of using this path, than taking their maximum value. Note, however, that if both the T_1 and I_1 metrics are used, the algorithm has exponential complexity, while when one them is replaced by the T_∞ and I_∞ metrics, respectively, the complexity is polynomial.

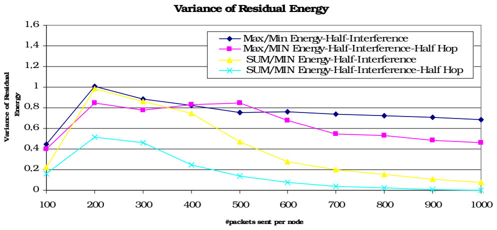

Figure 7: Variance of the residual energy at the end of an evacuation problem.

VI. CONCLUSIONS

We proposed and analyzed several interference and energy-aware routing algorithms for ad-hoc networks that use power control. The algorithms proposed use the multicost routing approach, where a vector of cost parameters is assigned to each link or path. This is very different from (and gives different results than) single cost routing, where a scalar cost (that may be a function of several cost parameters) is assigned to each link and path. Multicost routing enables us to easily examine and implement a large number of different algorithms, each optimizing a different cost function. We evaluated the algorithms proposed by looking at both delay and energy related performance metrics. We found that the algorithms, that incorporate hop count, interference and energy related metrics give the most balanced results. The function optimized, however, and the algorithm to be used, should not depend only on the examined performance metrics which represent the interests of the network, but also on the QoS requirements of the user.

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