Balancing Power: Tradeoffs between Connection Lifetime and Control Traffic in MANETS

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ABSTRACT

We present new power distribution schemes on an active route in wireless ad hoc networks, with the objective of maximizing connection lifetime against node mobility. Through experiments with each of the proposed power distribution schemes, we obtain a description of the relationship between control traffic overhead and their expected gains in connection lifetime, as well as an understanding of the influence of various system parameters (e.g. connection size, node density, and power budget size) on this relationship.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design–*wireless communication*

General Terms

Algorithms, Performance

Keywords

Ad-hoc, mobility, connection lifetime, power control

1. INTRODUCTION

Link breakage due to node mobility is a severe problem in wireless ad hoc networking. Such disconnections on active routes generally increase traffic overhead in the network layer, and cause packet losses in the link layer. In this study, we exploit the transmission power control in order to prevent link disconnections, and thus maximize of connection(path) lifetime against node mobility. We take connection lifetime to be the time during which its constituent links are operational. A link ceases to be operational when the autonomous movement of one of the link's endpoints causes it to fall out of transmission range of the other endpoint.

We presume that energy supplies at the nodes are renewable. Notice that we are not trying to increase spatial reuse nor energy efficiency. Specifically, we assume that each connection in a network has a certain ***power consumption budget*** which can be distributed among the nodes on the connection [2, 3]. We describe new power budget distribution schemes which seek to increase connection robustness in mobile environments.

The budgeted power model was initially introduced by Khan in [2]. Later, in [5], the authors designed a decentralized power budget redistribution protocol that minimizes end-to-end connection BER. Then, in [1] the authors developed analogous protocols to maximize the expected connection lifetime. In this paper, we refine our prior results on maximizing connection lifetime by considering *both the time and traffic required in operating the control protocols themselves.*

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2. PROBLEM DEFINITION

Consider a single connection between a source node ***s*** and a destination node ***t***, and assume that a transmission power budget ***P*** has been specified for this connection. The questions arise: (i) How should P be distributed among intermediate nodes of the connection if the objective is to maximize the expected value of the connection lifetime? (ii) How does such a power distribution scheme perform relative to a scheme which simply allocates power in a uniform static manner among the constituent nodes? In answering these questions, we normalize the proposed schemes with respect to the control traffic utilized by the power distribution schemes themselves.

Model. We consider a wireless ad-hoc network $G = (V, E)$ consisting of $|V|$ mobile nodes each assigned a unique ID i in $\{1, \ldots, |V|\}$ and equipped with omni-directional antennas that can dynamically adjust their transmission power [2, 3, 5]. If node i transmits with power $P_t(i)$, the power of the signal received by node j is given by $P_{rcv}(j) = \frac{P_t(i)}{c \times d_{ij}^{\alpha}}$, where d_{ij} is the distance between nodes i and j, and α, c are both constants, and usually $2 \leq \alpha \leq 4$ (See [4]). In order to correctly decode the signal at the receiver side, it is required that $P_{rcv}(j) \geqslant \beta_0 \times N_0$, where β_0 is the required signal to noise ratio (SNR) and N_0 is the strength of the ambient noise. We denote the minimum signal power at which node i is able to decode the received signal as $P_{min} = \beta_0 \times N_0$.

3. POWER DISTRIBUTION SCHEMES

We describe schemes that continuously redistribute the power budget assigned to a connection among its constituent mobile nodes, so as to postpone link disconnections and maximize connection's expected lifetime. The proposed schemes are implemented on top of any routing protocol that can

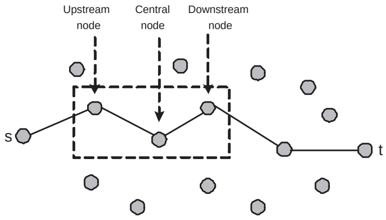

Figure 1: Multi-hop path description

provide an initial path within power budget constraints.

3.1 Uniform Scheme

Given an N-node connection between nodes s and t having total power budget P, the *Uniform* power distribution scheme allocates power uniformly to each of the $N-1$ nodes (excluding the destination node) $P_{unif}(j) = \frac{P}{N-1}$.

3.2 MinBER Scheme

This power budget distribution protocol was developed by the authors previously [5]. The protocol operates on *all* (overlapping) consecutive triplets of nodes within the connection, where in each triplet, we denote the nodes as the upstream node, the central node, and the downstream node—this naming convention is illustrated in Figure 1.

A node enters the protocol by simultaneously sending an Update message to its upstream and downstream neighbors. The Update message describes its present transmission strength. A node receiving an update uses its contents and the actual received signal strength to deduce an estimate of the distance to the sender of the Update. Thus each node (viewed in its central role) maintains estimates of distance to upstream and downstream nodes. When the central node receives an Update message informing it of the transmission power and (implicitly) distance to a neighbor, it redistributes power between itself and the upstream node so to minimize the BER of the two hop sub-path from its upstream neighbor to its downstream neighbor. This local optimization is computed using the analytic model of BER presented in [5]. This process occurs concurrently between all (overlapping) triplets of nodes via a distributed protocol, and ends when the power exchanged drops below a specified threshold; we denote the resulting power distribution at node j as $P_{BER}(j)$.

3.3 Sqr Scheme

Power is allocated based on the square of the distance to the next hop along the path towards the destination node. In a connection between nodes s and t with length $N-1$ hops and a total power budget P, each node j will be allocated

$$P_{sqr}(j) = P \cdot d_j^2 / \sum_{i=1}^{N-1} d_i^2,$$

where d_j is the distance from node j to node $j+1$ along the path. The protocol runs continuously to keep power values updated in light of node mobility. The protocol strives to keep received signal power at each node identical, thereby ensuring all links have the same stability. The implementation is as follows:

In phase 1, the source node initiates a control message including its Tx power information and sends it to the next hop towards the destination node. At the next hop the receiver deduces the distance to the sender by comparing Tx and Rx levels, then inserts its own Tx level into the message, updates the cumulative square-distance field, and forwards it to the next hop. This process repeats; when the message is delivered to the destination, $\sum d_i^2$ is known. In phase 2, the destination initiates another control message containing $\sum d_i^2$ and sends it to the source node, allowing all transit nodes to learn the value. In order to prevent budget violations, only reductions of power are carried out in phase 2; increases are carried out in a third phase, in reaction to a control message from the source to the destination.

In theory all links should break simultaneously for the *Sqr* scheme. In practice, however, because the control protocol takes time to converge, shorter links have a smaller radius of safety, which are more sensitive to node mobility, and so break earlier than longer links. This leads us to the next scheme.

3.4 Safe Scheme

The power budget is distributed among the nodes so that the safe distance of every node is equal, where safe distance is defined as the minimum distance for a node to go out of the coverage area of its upstream neighbor (see Figure 2).

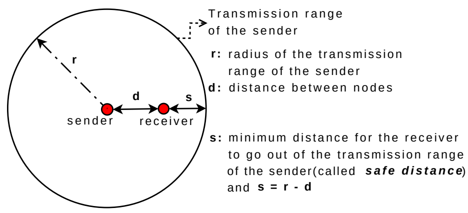

Figure 2: Safe scheme description

Implementation of this protocol is similar to *Sqr* scheme's implementation, however because computing the safe distance of each node requires all distance values between nodes to be known (not just their cumulative value as in *Sqr* scheme), the message initiated by the source node in phase 1 keeps a distance vector rather than just one cumulative value. This makes the resulting message grow linearly in size as it traverses the connection. In addition, in phase 2, the destination must inform each node individually about its new power Tx values. Because of these reasons, control message traffic is higher and convergence time is longer than for *Sqr*.

3.5 ModSqr Scheme

This scheme is a modification of the *Sqr* scheme with the following power distribution formula.

$$P_{sqr}(j) = P \cdot (d_j + c)^2 / \sum_{i=1}^{N-1} (d_i + c)^2,$$

where c is a constant (taken as 3 meters in this study), d_j is the distance from node j to node $j+1$ along the path. Note that *ModSqr* is a continuous parametric family spanning the *Sqr* ($c = 0$) and *Uniform* ($c = \infty$). The control traffic required to implement *ModSqr* is comparable to that of *Sqr* since only a cumulative value needs to be conveyed.

4. EXPERIMENTAL SETUP

Initial network design. In our simulations, we consider connections where the nodes were placed randomly according to the following inductive process: If node j is located at (x_j, y_j), then node $j+1$ is located at $(x_{j+1}, y_{j+1}) = (x_j + d_x, y_j + d_y)$ where d_x, d_y are uniformly distributed in the interval $[0, D]$. For most experiments (except when considering the effect of node density) we took $D = 100$ meters. The simulation is realized at packet level such that each node handles one either data or control packet at each simulation step, assuming that there is spatial reuse. We considered two different lower layer implementations in these experiments:

- *Soft TDM (Time Division Multiplexing) Mode:* There are an ε fraction of the time slots assigned to carry control traffic, but these slots can be used for data traffic if there is no control packet to be forwarded.

- *Hard TDM Mode:* As above, except control slots cannot be reallocated to carry data packets.

Mobility model. Nodes are allowed to move according to a Cartesian random walk mobility model [6]. Each node has five possible directions in which to move at a certain movement frequency, of which one is selected uniformly at random: it may go north, south, east, or west 1 meter at each movement, or to stay at the current position until the next movement. For instance, movement frequency = 100 means that the nodes move after every 100 packets handled at a node.

Performance measures. As performance, we take the number of data packets received by the destination node before the connection breaks. The gain of a power distribution scheme is calculated by comparing its performance against that of the *Uniform* scheme. We conduct 10^3 independent trials, each trial beginning with a different random initial network and movement sequence; aggregate metrics are then computed as averages over the trials:

$$\text{Gain}_A = E[\frac{\text{Number of the data messages of Scheme A}}{\text{Number of the data messages of Unif}}]$$

System and environmental parameters. We explore the impact of these situational parameters on gain of each scheme:

A. *Number of nodes N:* We vary the number of nodes on the path ranging from few (5) to many (25) nodes.

B. *Power budget P:* We consider connection power budgets ranging from small (3.0 Watts) to large (10.0 Watts).

C. *Initial node density δ:* We vary node density in the initial network from sparse (0.01 nodes/m) to dense (0.05 nodes/m). This is achieved by taking $N = 500 * \delta$ and scaling the network geometry proportionally so that the initial network is bounded by the 500 meter square.

D. *Control time slots percentage ϵ:* This parameter determines what percentage of total time slots are assigned for control traffic, ranging from 0 to 100. We fixed this value as 0.2 (20%) for all experiments except the last experiment, gain vs ϵ.

Fixed parameters. We consider *movement frequency* to be fixed, at one movement every 200 packet transmissions, for each node. The *Signal attenuation exponent* α was taken as 2, appropriate to our connection distance scales in free space. The minimum signal power at which a receiver is able to decode a signal is taken as $P_{min} = 10$ mW.

5. SIMULATION RESULTS AND ANALYSIS

We conducted experiments to quantify the influence of the number of nodes N, connection power budget P, initial node density δ, and control traffic overhead ϵ, on the expected gain of the schemes over the *Uniform* scheme.

Note: In cases where pairs of curves in our graphs lie within one standard deviation of each other's points, we provide the ***correlation coefficient*** between the per-trial gains of the two schemes, so as to justify any conclusions based on the relative geometry of the two curves.

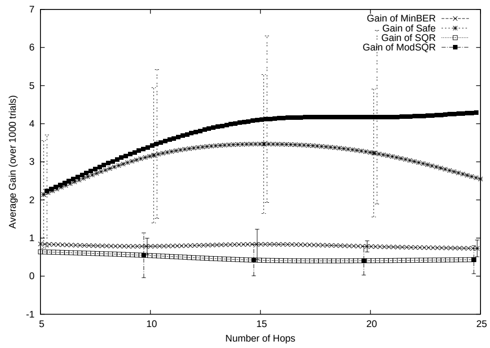

Figure 3: The Influence of Number of Hops on Gain in Soft TDM Mode

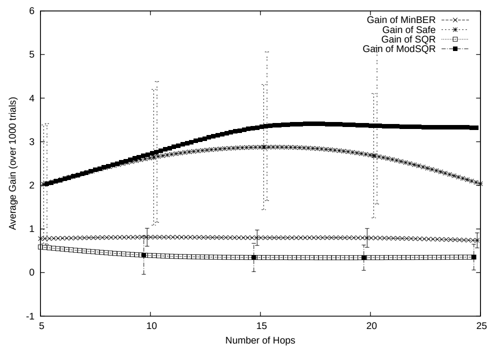

Figure 4: The Influence of Number of Hops on Gain in Hard TDM Mode

A. Varying the connection size. In the first set of experiments, we varied the connection size from 5 to 25 nodes, while keeping all other variables fixed: the power budget (P) was fixed at 10.0W, and the initial mean node density was one node every 100m.

There are three significant factors (which depend on the number of hops) that affect gain: (i) the collective resources available to the nodes to compensate for weak links, (ii) the convergence time of the control protocol (especially for end-to-end operations), and (iii) control traffic overhead of the schemes. For *ModSqr* scheme, as the number of hops increases, the factor (i) increases faster than (ii), while (iii) is remains constant per node. *ModSqr* enjoys a linearly growing gain up to the connection size of 15, after which the first two factors balance each other, and the curve becomes flat as in Figure 3 and 4. For *Safe* scheme, factor (ii) begins to dominate factor (i) because increased message complexity causes the convergence time of *Safe* scheme to grow quadratically in connection size. The correlation between *ModSqr* and *Safe* was (0.98), showing that the former genuinely outperforms the latter, in spite of the fact that the two curves lie within each other's error bars. The gain of *Minber* is independent of the connection size because it works within triplets and it does not use an end-to-end protocol. Finally, *Sqr* and *minBER* were the worst scheme in terms of gain as seen in the figures. *Sqr* performs poorly because it leaves short connection links disproportionately vulnerable to endpoint mobility. *minBER* performs poorly because its objective is orthogonal to expected longevity. The correlation between *MinBER* and *Sqr* was (0.21) indicating that the schemes cannot be compared to each other, as they lie within each other's error bars.

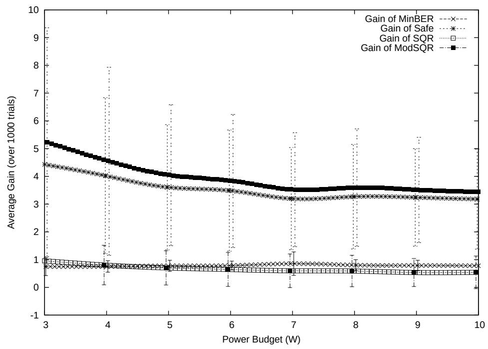

Figure 5: The Influence of Power Budget on Gain in Soft TDM Mode

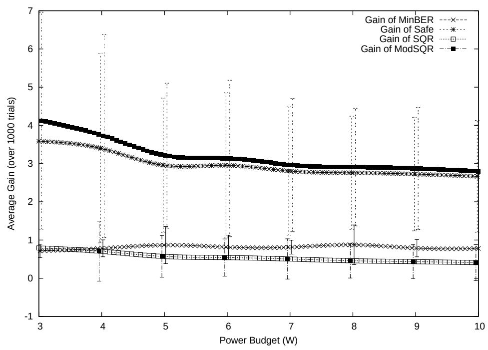

Figure 6: The Influence of Power Budget on Gain in Hard TDM Mode

B. Varying the power budget. In the second set of experiments, we varied the connection's power budget from 3.0W to 10.0W, while keeping all other variables fixed: the number of nodes (N) was fixed at 10, and mean node density was one node every 100m.

Clearly the gains of the schemes should approach 1 as the power budget goes to infinity. This intuition is born out in Figures 5 and 6. In spite of this, ModSqr and Safe schemes outperform the Sqr and minBER schemes, providing a gain of over 300% even for very high power budgets.

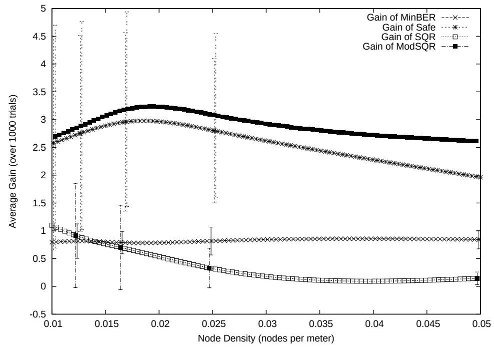

Figure 7: The Influence of Node Density on Gain in Soft TDM Mode

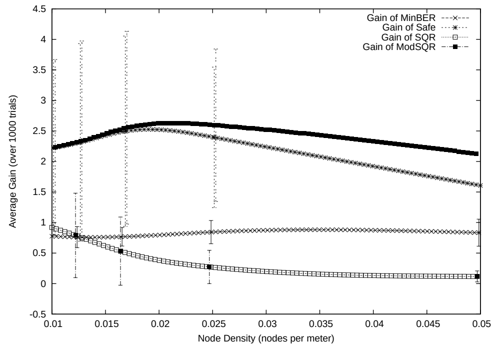

Figure 8: The Influence of Node Density on Gain in Hard TDM Mode

C. Varying the node density. In the third set of experiments, we varied the node density from one node every 100m ($\delta = 0.01$ nodes/meter) to one node every 20m ($\delta = 0.05$ nodes/meter), while keeping all other variables fixed with the power budget (P) of 10.0W. The number of nodes N was taken to be 500δ, and the initial configuration was rescaled proportionately so that it was bounded by a 500m by 500m square.

This experiment is closely related to the investigations of hop size since changing node density implies changing hop size of a connection. The results of both experiments thus look similar (Figure 7 and 8) and the interpretations made in the hop-size experiment are also valid here. The correlation between *ModSqr* and *Safe* was (0.95), showing that the former genuinely outperforms the latter, in spite of the fact that the two curves lie within each other's error bars. The *Sqr* scheme exhibits better performance when node density is low since when the nodes are denser the probability of having short links gets higher. As noted earlier, *Sqr* causes nodes with short links to adjust their power level so that receiver nodes are at the precipice of the transmission radius (i.e. their safe distance is very small); this yields early disconnections of short links.

D. Varying the control traffic overhead. In the final set of the experiments, we varied the control traffic overhead by changing fraction of slots (ε) allocated to control traffic,

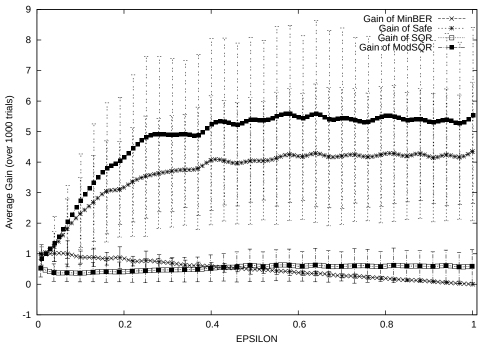

Figure 9: The Influence of Control Traffic on Gain in Soft TDM Mode

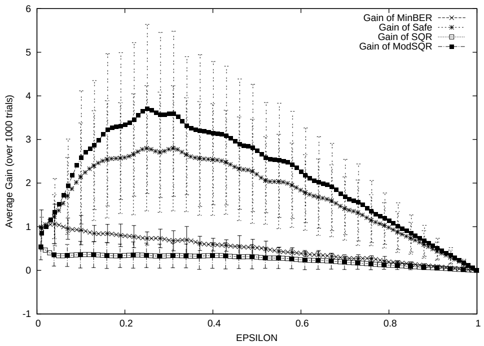

Figure 10: The Influence of Control Traffic on Gain in Hard TDM Mode

while keeping other variables fixed: power budget (P) was fixed at 10.0W, the number of nodes (N) was fixed at 10 , and the mean node density was one node every 100m.

Figure 9 shows the effect of *Epsilon* on the gain in Soft TDM mode. *ModSqr* and *Safe* show similar response herein, but *ModSqr*'s gain is higher than *Safe*'s gain since *Safe* has higher control traffic (and hence longer convergence times) than *ModSqr*. Note that the correlation between *ModSqr* and *Safe* was (0.97), showing that the former genuinely outperforms the latter, in spite of the fact that the two curves lie within each other's error bars. Both curves initially rise linearly up to around ε=0.25, then remain flat. When the ε is too small, there are few control time slots and the schemes run and converge slower than the side effects of node mobility, resulting in lower performance. Once the percentage of control time slots reaches a reasonable value (at about ε=0.25) the schemes obtain maximum gain level and increasing ε beyond this yields nothing in terms of the gain. Assigning too large an ε is both useless and *harmless* due to fact that the schemes is already converged and the nodes are allowed to handle data packets in the absence of control packets respectively in Soft TDM. In the same figure, the gain of *MinBER* decreases linearly as ε increases, and when ε=1.0 its gain becomes zero; this is understandable since in *minBER* the nodes always have control messages to send and will thus swamp out data if given the opportunity. The correlation between *minBER* and *Sqr* was low (0.13), indicating that the two schemes are incomparable, since their curves lie within each other's error bars. Figure 10 considers the effect of varying ε in Hard TDM mode. The correlation between *ModSqr* and *Safe* was (0.99). According to the figure, there are tradeoffs for *ModSqr* and *Safe* schemes such that they reach their maximum gain values when ε=1/4. As ε increases to 1.0 the gains of the all schemes decrease linearly and approach 0, since in Hard TDM control slots will swamp out data slots if ε is set too high.

6. CONCLUSION

The *Sqr* scheme equalizes received power levels at all nodes, and so is theoretically optimal in settings where the power distribution protocols operate instantaneously. In practice, however, it is seen to perform poorly when convergence time take into consideration. This realization motivated the design of the *Safe* scheme, which seeks to equalize the safe distances of nodes–that is, the distance that any node can move without breaking the connection. While the *Safe* scheme computes an optimal solution, it is crippled by its high communication complexity (and hence slow convergence in TDM implementations); this motivated the development of the *ModSqr* scheme, which captures the gains of *Safe* without incurring the high communication costs. We have implemented all schemes with two different lower layer assumptions: (i) *Soft TDM mode*, that is, there are control time slots for control traffic, and these time slots can be used on behalf of data traffic if there is no control packet to be forwarded at the nodes. (ii) *Hard TDM mode*, that is, there are again control time slots assigned for control traffic, but this time the nodes are not allowed to handle data packets if there is no control packets in the control time slots.The investigations demonstrate that taking control traffic overhead and convergence time of protocols play a critical role in the analysis of the proposed schemes.

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