Minimizing Wireless Connection BER through the Dynamic Distribution of Budgeted Power

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Abstract— **We develop a new dynamic scheme which continuously redistributes a fixed power budget among the wireless nodes participating in a multi-hop wireless connection, with the objective of minimizing the end-to-end wireless connection bit error rate (BER). We compare the efficacy of our scheme with two static schemes: one that distributes power uniformly, and one that distributes it proportionally to the square of inter-hop distances. In our experiments we observed that the dynamic allocation scheme achieved superior performance, reducing BER by using its ability to distribute the power budget. We quantified the sensitivity of this performance improvement to various environmental parameters, including power budget size, geographic distance, and the number of hops.**

Index Terms— **wireless ad-hoc networks, multi-hop path, bit error rate, power budget, optimal power distribution.**

I. Introduction

New distributed computing/communication applications drive the energy requirements of wireless ad-hoc systems ever upwards, while simultaneously, the batteries which power wireless devices present a hard constraints on the operation of mobile computing systems. Recent developments in devices with tunable transmission power enable us to manage the tension of power supply and power demand using dynamic power redistribution schemes. In this paper, we present results of recent investigations along this avenue. Our objective is to optimize the bit error rate (BER) of connections—and hence the packet-level error rate (PER) experienced at the network layer. Since many applications require a minimal Quality of Service (QoS) to guarantee acceptable responsiveness, such an improvement can greatly benefit network function.

Historically, reconciling the gap between power consumption and supply involved [14] solving the following issues: (i) improving the power efficiency in the system; and (ii) preventing the system deconstruction due to unfair power usage. In our earlier work [2], [3], we proposed addressing these issues through the principle of *optimal allocation of budgeted power*; we introduced a model in which every connection request is assigned a fixed *power budget* to support its instantiation. In this paper, we present a scheme which dynamizes these approaches by enabling the redistribution of a power budget among the constituent nodes in a multi-hop connection, with the objective of minimizing the wireless connection BER.

Standard models of *wireless ad-hoc* networks typically consider infrastructure-less networks in which every node assumes the role of both a host and router, and every node is mobile. In this paper, we will not consider mobility-related issues. Although our investigation makes the simplifying assumption of a scenario in which mobility does not greatly impact power allocation decisions, the conclusions we present are nevertheless significant in the broader context of power management in wireless and ad-hoc networks.

The remainder of the paper is organized as follows. We begin in Section II with an exposition of prior related research work. Then, in Sections III and IV we define the problem and the presumed network model. In Section V, we describe the protocol by which power is redistributed dynamically, to attain minimum BER. In Section VI we describe the experimental setup, and then analyze the results of the simulation study in Section VII, by comparing the proposed protocol against other traditional power distribution schemes.

II. Related Work

Approaches for efficient power management have been investigated at various protocol layers by several researchers, (e.g. see [14], [13], [4]) 1. At the *Physical layer*: Using directional antennae, applying knowledge of spatial neighborhood as a hint in setting transmission power; 2. At the *Data-link layer*: Avoiding unnecessary retransmissions, avoiding collisions in channel access whenever possible, allocating contiguous slots for transmission and reception whenever possible; 3. At the *Network layer*: Considering route-relay load, considering battery life in route selection, reducing frequency of control messages, optimizing size of control headers, route reconfiguration; 4. At the *Transport layer*: Avoiding repeated retransmissions, handling packet loss in a localized manner, using power-efficient error control schemes.

One broad category of solutions consists of energy aware routing protocols (e.g. see [13], [6], [8]). In wired networks, the emphasis has traditionally been on maximizing end-to-end throughput and minimizing delay. To maximize the lifetime of mobile hosts, however, routing algorithms must select the best path from the viewpoint of power constraints and route stability. Routes requiring lower levels of power transmission are generally preferred, but this can adversely affect end-to-end throughput. Transmission with higher power increases the probability of successful transmission, although high power strategies also result in more cross-node interference, destroy existing transmission bands, and thus cause the network to have blocked connections. In [5] and [1], Banerjee and Misra showed that energy-aware routing algorithms that are solely based on the energy spent in a single transmission are not able to find minimum energy paths for end-to-end reliable

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packet transmissions, in both End-to-End and Hop-by-Hop retransmission settings.

Our own prior work [3] was a natural extension of Misra [1] and Banerjee [5], reframed by normalizing experimental scenarios using a fixed power budgets for each connection. In [2], we presented an experimental evaluation of those techniques, showing how data replication along multiple paths can be used to lower packet error rate of application layer connections in wireless ad-hoc networks under power budget constraints.

This work begins at the point where energy aware routing ends. Here we propose a new dynamic scheme that continuously redistributes the power budget among all nodes across a multi-hop wireless connection with the objective of minimizing the wireless connection BER.

III. Problem Definition

Consider a single connection request 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 question to be answered is *how should P be distributed among intermediate nodes of the connection if the objective is to minimize the end-to-end connection bit error rate?* We shall assume, as assumed in other similar investigations (e.g. [11]), that each node has the ability to send with dynamically tunable transmission power, and that node mobility is insignificant when compared to routing convergence times. The proposed dynamic power distribution protocol is implemented on top of a routing protocol that is responsible for providing a multi-hop path between s and t, within total power budget constraints—designing such an energy-aware routing protocol is beyond the scope of this paper.

Our design idea is founded on the simple observation that in a multi-hop path the distance between two consecutive intermediate nodes varies on a hop-by-hop basis. For nodes which are a short distance from each other, less power can be allocated while still attaining good channel bit error rate. When two consecutive nodes are far from each other, a weak transmission power would result in a high wireless channel bit error rate. We present a dynamic power redistribution scheme based on geographical distance, which allows nodes to negotiate the amount of power they use (while remaining within connection budget constraints) thereby optimizing overall connection bit error rate.

IV. Network Model

We consider a wireless ad-hoc network consisting of N nodes equipped with omni-directional antennas that can dynamically adjust their transmission power. We model this network as a linear geometric graph $G = (V, E)$, where V is the set of nodes and E is the set of edges. Each node is assigned a unique ID i in $\{1, \ldots, |V|\}$, and node i can send data with a dynamically tunable transmission power in the range $[0, P_{max}(i)]$.

Wireless propagation suffers severe attenuation [5] and [12]. If node i transmits with power P(i), the power of the signal received by node j is given by

$$P_{rcv}(j) = \frac{P_t(i)}{c \times d_{ij}^{\alpha}}, \tag{1}$$

where d_{ij} is the distance between nodes i and j. α and c are both constant, and usually $2 \leq \alpha \leq 4$ (See [5]). In order to correctly decode the signal at the receiver side, it is required that

$$P(j) \geqslant \beta_0 \times N_0, \tag{2}$$

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}.

Each link (i, j) has a computable bit error rate $BER(i, j)$, which represents the probability of the occurrence of an error during the data transfer over that link. The relationship between the bit error rate BER over a wireless channel and the received power level P_{rcv} is a function of the modulation scheme. It can be expressed in general as follows [5].

$$BER \propto Q\left(\sqrt{\frac{P_{\text{rcv}} C t^e}{f\ P_{\text{noise}}}}\right), \tag{3}$$

where P_{noise} is the noise spectral density, f is the raw channel bit error rate, and $Q(x)$ is defined as follows.

$$Q(x) = 1 - \frac{2}{\pi}\int_0^x e^{-t^2}\,dt. \tag{4}$$

Since we are only interested in studying the general dependence of the bit error rate on the received signal power, we will consider the non coherent binary orthogonal Frequency Shift Keying (FSK) modulation scheme. Other modulation schemes can be analyzed in similar way, however closed-form analysis may not be always possible. For this specific modulation scheme, the instantaneous channel bit error rate BER is given by [9], [10], [7] to be:

$$BER = \frac{1}{2}\, e^{-\frac{P_{\text{rcv}}}{2P_{\text{noise}}}} \tag{5}$$

A path consisting of a sequence of links $L_1, \ldots, L_r$ has a BER equal to $1 - \prod_{\ell=1}^{r} 1 - BER(L_\ell)$

V. Dynamic Scheme

The proposed protocol operates on *all* (overlapping) consecutive triplets of nodes within the connection (s, t). Within each triplet, we denote the nodes to 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 determines the optimal

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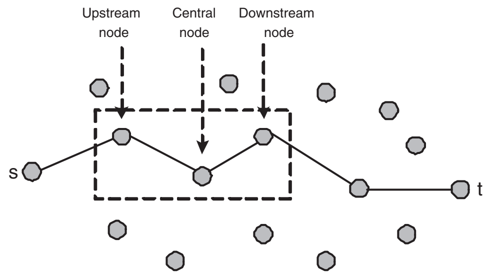

Fig. 1. Multi-hop path description

redistribution of power between itself and the upstream node. This local optimization is computed on the basis of the analytic BER model presented in the previous section. In effect the central node acts greedily to minimize the BER of the two hop sub-path from its upstream node to the downstream node. If the local optimization shows that a significant redistribution of power is required, and this redistribution will not cause the received signal strength to drop below P_{min} at any node, then the central node is able push power downstream (Figure 2) or push power upstream (Figure 3). It accomplishes this by Power Request and Power Transfer messages, respectively. Receipt of a Power Request always causes a node to reduce its transmission power and reply with a Power Transfer Message. Receipt of a Power Transfer Message always causes a node to increase its transmission power and reply with a Ack Message. Receipt of Ack and Update Messages always result in further propagation of an Update Message. The power reallocation process is negotiated concurrently between all (overlapping) triplets of nodes via a distributed protocol. The protocol is said to have converged if the total power exchange drop below a user specified threshold. In the rest of this paper, we will refer to the converged distribution attained by this distributed protocol as the *Dynamic* scheme. We compare the performance of the dynamic protocol against two static schemes.

A. Uniform Scheme

Given a connection between nodes s and t with length $k+1$ hops and a total power budget P. The uniform power distribution scheme consists of allocating to each of the k nodes (excluding the destination node) a uniform fraction of the total power $P_{unif} = \frac{P}{k}$.

B. Sqr Scheme

Under this power distribution scheme, the power is allocated based on the square of the distance to the next hop along the path towards the destination node. Specifically, given a connection between nodes s and t with length $N-1$ hops and a total power budget P, each node j will be allocated a power P_{sqr} such that $P_{sqr} = Pd_j^2/\sum_{i=1}^{N-1} d_i^2$, where d_j is the distance from node j to node $j+1$ along the path.

VI. Experimental Setup

In our simulations, we consider networks where the intermediate nodes are randomly distributed along a line between

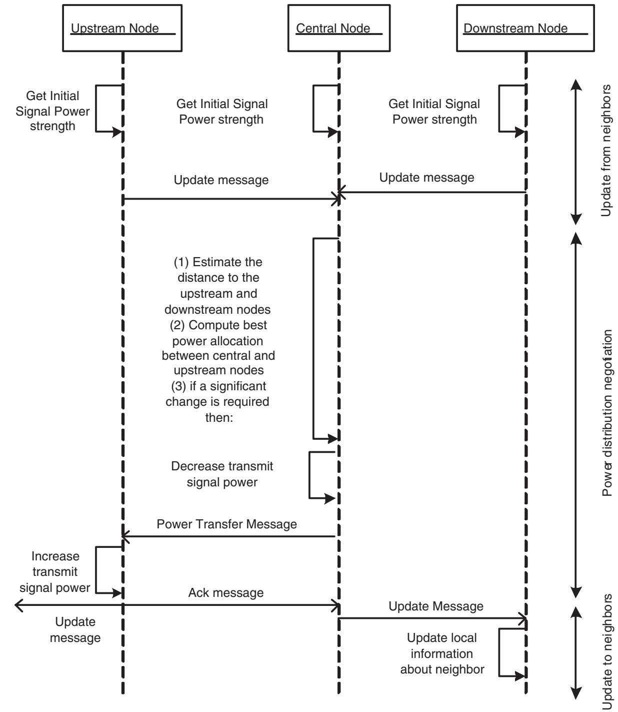

Fig. 2. Event sequence diagram: pushing power upstream

two end points. During the experiment, all network parameters involved in the system are kept in the following ranges:

- *Path Length*: We consider path lengths ranging from short (5 intermediate nodes) to long (25 intermediate nodes).
- *Power budget*: We consider connection power budgets ranging from small (1 Watt) to large (10 Watts).
- *Distance*: We consider scenarios in which the two end-points range from nearby ($100m$) to distant ($400m$).
- α: A scaling constant is kept fixed at 2, as appropriate to our connection scales.
- SNR: The Signal to Noise Ratio of the wireless channel is kept fixed at 1mW, as appropriate to a typical SNR value for wireless channel.

The graphs in the next section depict the average values collected from 10^4 trial runs of each experiment scenario. We demonstrate how protocol optimally distributes this budget among the nodes of the multi-hop path under consideration.

VII. Results and Analysis

To begin, we study the impact of the variance in inter-node distances on the improvement (in connection BER) achieved by the *Dynamic* scheme when compared to the *Uniform* scheme. Intuitively, one might expect that in a high variance scenario the dynamic power distribution would outperform uniform allocation of power, because the negotiation process would converge to a significantly different power distribution. However, Figure 4 shows that the effects are more subtle and cannot be captured by a single parameter of variance. For instance, for a variance value of $37m$, the improvement varies from 4% to 24%. Similarly, when the variance is small (say $7m$), the improvement varies from 3% to 17%. We conclude

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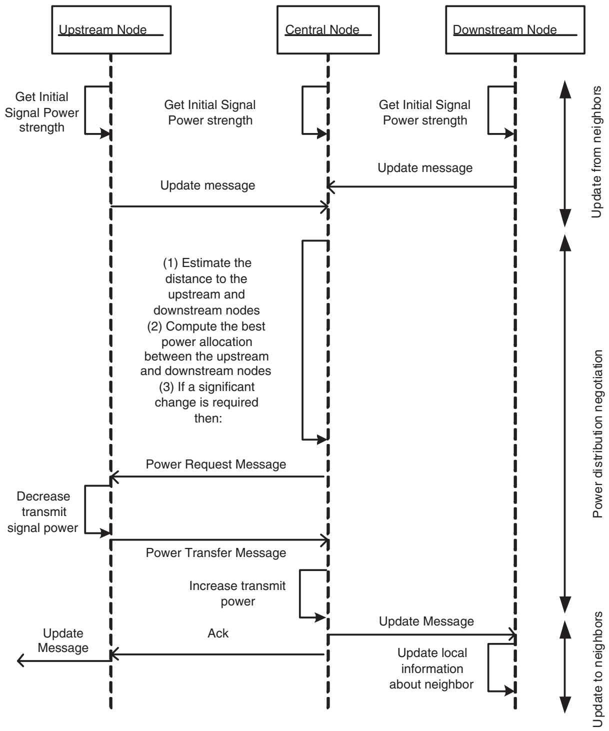

Fig. 3. Event sequence diagram: drawing power downstream

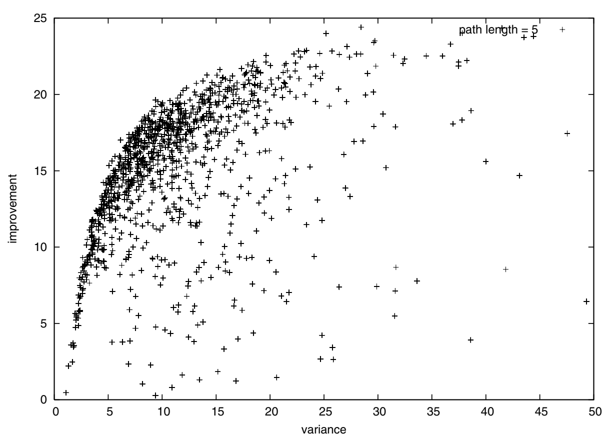

Fig. 4. Percentage improvement of *Dynamic* over *Uniform* vs. variance

that the performance of the dynamic scheme is not well-modeled by a coarse measure such as variance.

We compare the performance of our *Dynamic* scheme with both the *Uniform* and the *Sqr* schemes. For each of these schemes, we study the impact of considering different path lengths, connection power budgets, and end point distance. The legends of each curve indicate the average relative performance of two schemes. For example in Figure 5, the curve titled *Dynamic/Sqr* shows the average value of the quantity

$$\frac{BER(Sqr) - BER(Dynamic)}{BER(Sqr)}.$$

The fact that this curve passes through the point $(8000mW, 40\%)$ indicates that when the power budget was $8W$, the BER achieved by *Dynamic* was (on average) 40% lower than what was achieved by *Sqr*, over the 10^4 trials

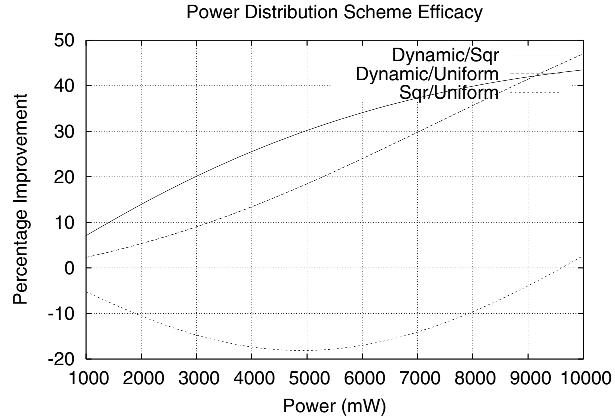

Fig. 5. Percentage improvement vs. total connection power budget

conducted at that power setting. Similarly, the curve indicates that with a $5W$ power budget, *Sqr* performed almost 20% worse than *Uniform*.

Figure 5 illustrates the impact of the power budget on the performance of each power allocation scheme. The distance between endpoints was fixed at $120m$, and the number of intermediate nodes was fixed at 9—thus the average internode spacing was approximately $12m$, in the range of present $54Mb/s$ wireless technology. Considering the *slopes* of these curves we conclude that the improvement of the *Dynamic* scheme relative to the *Uniform* and the *Sqr* schemes increases as the total connection power budget increases. For example, comparing *Dynamic* to *Sqr*, we see that at $1W$ power budget *Dynamic* outperforms *Sqr* by 8% in terms of BER, while by $9W$ the improvement rises to 40%. We note, however, that the relative performance of *Uniform* and *Sqr* schemes is not monotone: when the power budget is small, the *Sqr* scheme outperforms the *Uniform* approach, but as the power budget increases to $10W$, the conclusion is reversed. Comparing the *heights* of the curves, we conclude that the proposed dynamic scheme outperforms both of the other power allocation techniques in both fair and good wireless channel conditions.

Figure 6 illustrates the impact of varying the distance between the connection end points, while keeping constant both the number of intermediate hops and the total power budget. The connection power budget was fixed at $2200mW$, and the number of intermediate nodes was fixed at 10—thus the average node transmission power was approximately $220mW$, in the range of present $54Mb/s$ wireless technology. Considering the *slopes* of these curves we conclude that the improvement of the *Dynamic* scheme relative to the *Uniform* and the *Sqr* schemes decreases as the total distance increases. For example, comparing *Dynamic* to *Sqr*, we see that at $100m$ distance *Dynamic* outperforms *Sqr* by 16% in terms of BER, but at $200m$ the improvement drops to 3%. We note, however, that the relative performance of *Uniform* and *Sqr* schemes is not monotone: The lower curve of Figure 6 reaches a local minimum at distance $110m$. At connection distances below this critical value, the improvement of *Uniform* over *Sqr* decreases as the distance increase, but this behavior gets reversed for distances bigger than $110m$. By comparing the

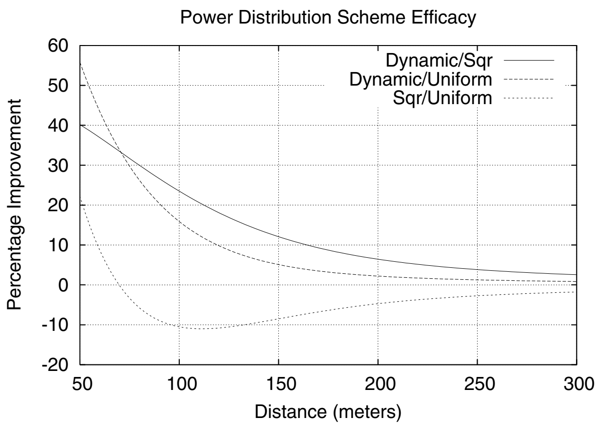

Fig. 6. Percentage improvement vs. total connection distance

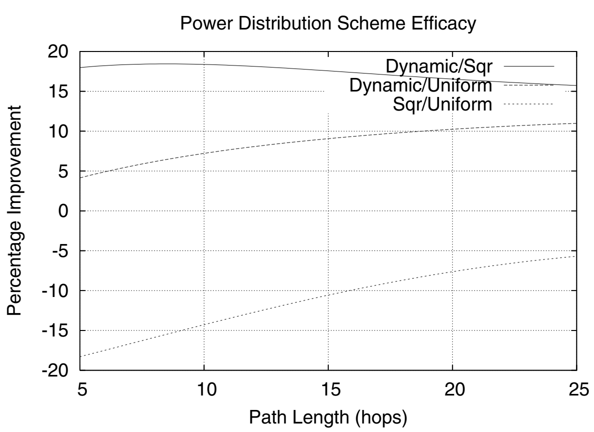

Fig. 7. Percentage improvement vs. connection length

heights of the curves, we conclude that the proposed dynamic scheme outperforms both of the other power allocation techniques in both small and large distances scenarios. As the distances become larger, the difference between power allocation schemes becomes immaterial.

Figure 7 illustrates the impact of varying the path length (in terms of the number of intermediate nodes) between the source and destination nodes while keeping constant both the distance between the connection end points and the total power budget. The connection power budget was fixed at $2200mW$, and the number of distance was fixed at $120m$–drawing upon the two experiment scenarios described earlier. Considering the *slopes* of these curves we conclude that the improvement of the the *Dynamic* scheme relative to the *Sqr* scheme lightly decreases as the number of the intermediate hops increases. However, in case of *Dynamic* versus *Sqr* and *Sqr* versus *Uniform* schemes, the improvement increases as the length of the path increases. For example, when considering a 10 hop path, *Dynamic* achieved an improvement of 7% over the *Uniform* scheme, while for a 20 hop path, the improvement was 10%. Comparing the *heights* of the curves, we conclude that the proposed dynamic scheme outperforms both of the other power allocation techniques for both short and long paths scenarios.

VIII. Conclusion and Future Work

In all the experiments, the dynamic allocation scheme achieved superior performance relative to the uniform and distance-squared proportional schemes. This improvement resulted from the dynamic scheme ability to reduce the BER by dynamically allocating the power budget among the intermediate nodes.

In all the experiments conducted, the proposed scheme was seen to converge in fewer than 10 iterations per node. The convergence rates and communication overhead was tunable by adjusting the definition of "significant change" in the protocol. Because we were not considering mobility, this cost was taken as the one-time initialization cost for the connection. In future, we intend to extend our consideration to the fully mobile setting. Because our power allocation protocol is decentralized and dynamic, it can react to node mobility by redistributing power in a manner which optimizes the BER. To evaluate the efficacy of the protocol in the mobile setting, we are presently conducting experiments to quantify the tradeoffs between convergence thresholds, control-traffic overhead, and resultant improvement in BER.

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