Weak Many vs. Strong Few: Reducing BER through Packet Duplication in Power-Budgeted Wireless Connections

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Abstract: In this paper we present new energy-aware techniques to lower the packet-level error rates of application-layer connections in wireless ad-hoc networks. We consider a model in which each connection is allocated a fixed power budget, and ask: Is it better to use this power budget to send many duplicate packets (at lower power) or fewer (e.g. just one) packets (at high power)? We consider a scheme in which each application-layer connection is implemented at the physical level by an overlay network consisting of multiple parallel multi-hop paths. Data packets submitted at the connection source are checksummed and replicated, flowing breadth-first across the overlay network towards the destination. The destination delivers the first error-free copy of each packet, in order, to the application layer, dropping packets that are corrupt or duplicate. We compare this overlay scheme with the traditional scheme in which the source transmits precisely one packet to the destination along a single minimum-hop path. We show that even when the two schemes are constrained by *identical power consumption bounds*, the overlay scheme can use duplication to attain significantly lower packet-level error rates in many common situations. We describe the relationship between packet error rate, the extent of duplication, and the lengths of the paths, and show that the qualitative nature of the relationships change significantly, depending on available power budget.

Keywords: wireless ad-hoc networks, overlay network, lower bit error rate, minimum energy consumption, node disjoint paths.

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Bilal Khan (M'04) has a M.S. in Computer Science from Johns Hopkins (1997) and Ph.D. in Mathematics from City University of New York (2003). He is Associate Professor of Mathematics, Computer Science, and Computer Forensics at John Jay College of Criminal Justice. Prior to this, he served as Principal Investigator in the High-Speed Networks Research Group, at the Center for Computational Sciences of the U.S. Naval Research Laboratory, as a contractor through ITT Industries.

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1 INTRODUCTION

The growing array of distributed computing/communication applications drives the energy requirements of wireless ad-hoc systems ever upwards. Simultaneously, the capacity of batteries which power most wireless devices presents a hard constraint on the operational lifetime of mobile computing systems. Not surprisingly, this tension of supply and demand makes the design of energy efficient wireless ad-hoc networks an important area of current research. Lowering energy consumption indiscriminately, however, often leads to undesirable side effects. Most notably, it can raise the bit error rate (BER) of links—and hence the packet-level error rate (PER) of application connections. Since many applications require a minimal Quality of Service (QoS) to guarantee acceptable responsiveness, such a degradation can yield the network functionally inoperative.

The management of power in multi-hop wireless networks is marked by the tension between: (1) the battery power available on the mobile node, and (2) the communication costs incurred, specifically the power required to transfer the data from one node to another. As summarized in Zhang and Liang (2003), reconciling the power gap between consumption and supply involves solving the following issues: (i) improving the power efficiency in the system; and (ii) preventing the system deconstruction due to unfair power usage.

In this paper, we consider the problem of how to balance the need for efficient energy allocation with the objective of low packet-level error rates. We propose 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 amount of power to support its instantiation[1].

Relatively little research has been conducted on quantifying the tradeoffs between power consumption and BER in ad-hoc networks under a fixed power budget model. This is our focus in this paper. 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 routing, the conclusions we present are nevertheless significant in the broader context of wireless and ad-hoc networks.

The remainder of the paper is organized as follows. We begin in Section 2 with an exposition of prior related research work. Then, in Section 3, we define the problem and our approach. In Section 4 we specify the network model and conduct a theoretical evaluation of the approach. In Section 5 we describe the algorithm by which minimum BER is achieved within power budget constraints. In Section 6, we describe the experimental setup in which the (n, k) algorithm will be evaluated. In Section 7, we present the results of our simulation study and compare the proposed algorithm against traditional schemes.

2 PRIOR WORK

Approaches for efficient power management in wireless networks, have been investigated at the various protocol layers by various researchers, including Robin and Krishnan (1998); Toh (2001); Zhang and Liang (2003). These efforts include attempts to address the problem at:

(1) *The Physical layer*: Using directional antennae, applying

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[1] In a more sophisticated version of the model, this budget might be related to a pricing scheme, so that connections could be supported in one of several power classes. Here we will keep the model simple, so as to extract more fundamental conclusions about its behavior.

knowledge of spatial neighborhood as a hint in setting transmission power,

(2) *The Data-link layer*: Avoiding unnecessary retransmissions, avoiding collisions in channel access whenever possible, allocating contiguous slots for transmission and reception whenever possible,

(3) *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, and

(4) *The Transport layer*: Avoiding repeated retransmissions, handling packet loss in a localized manner, using power-efficient error control schemes.

Topology control and management is one of the techniques used for efficient power usage, see e.g. Li et al. (2003). This approach consists of determining the transmission power of each node so as to maintain network connectivity while consuming the minimum possible power. Instead of transmitting using the maximum possible power, nodes in a wireless multi-hop network collaboratively determine their transmission power and define the topology of the wireless network by the neighbor relation under certain criteria. This is in contrast to the traditional network in which each node transmits using its maximum transmission power and the topology is built implicitly by routing protocols without considering the power issue.

Another approach for minimizing the power usage in wireless network is to reduce the amount of communication between nodes at the expense of extra computation. Most work focused on developing approaches that reduce the volume of data that need to be transmitted, typically through intelligent data reduction and aggregation techniques.

Another category of solutions have been proposed at the network layer, which consists of designing energy aware routing protocols, as reported in Christina and Krishna (2001); Li et al. (2001); Toh (2001). In wired networks, the emphasis has traditionally been on maximizing end-to-end throughput and minimizing delay. In general, paths are computed based on minimizing hop count or delay. Nonetheless, to maximize the lifetime of mobile hosts, routing algorithms must select the energy efficient paths. Hence, routes requiring lower levels of power transmission are preferred, but this can affect end-to-end throughput. Transmission with higher power increases the probability of successful transmission, thus increasing the end-to-end throughput. However, it also yields higher interference with other mobile hosts, which can destroy an existing transmission band and may cause the network to have blocked calls. This could result in a decrease in network capacity. Therefore, lower power transmission does not always have a negative impact on throughput. Since lower power transmission can reduce channel interference and contentions, it can increase end-to-end throughput. When power efficiency is considered, ad hoc networks will require a routing algorithm that can evenly distribute packet-relaying loads to each node to prevent nodes from being overused.

In Tang et al. (2004), the authors studied energy efficient algorithms for survivable broadcast/multicast routing, that are resilient to a single node failure. The network survivability was assured by applying redundant trees. The authors proposed the minimax survivable broadcasting/multicasting problems and the minimum survivable broadcasting/multicasting problem.

In Banerjee and Mirsa (2004); Dong and Banerjee (2005), the authors argued 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 packet transmissions. They considered the case of End-to-End Retransmission and Hop-by-Hop Retransmission. They have shown why the effective total transmission energy, which includes the energy spent in potential retransmissions is the proper metric for reliable and energy efficient communication.

In Jian and Xue (2004), the authors studied the tradeoff between the path lifetime and the total energy in wireless networks. They proposed two algorithms. The first algorithm constructs a pair of node disjoint paths whose total energy is minimum under the constraint that the lifetime is no smaller than a given threshold. The second algorithm computes a pair of node disjoint paths whose lifetime is maximum under the constraint that the total energy consumption is bounded by a given threshold. Their work was based on Srinivas and Modiano (2003), where they presented an efficient source transmit power selection algorithm, which finds the node disjoint paths with minimal total energy.

In Wu and Candan (2004), the authors showed that the performance of a protocol for an ad-hoc network can be enhanced if the protocol is designed based on overlaying a virtual infrastructure on the ad-hoc network. Therefore, in our current work, we propose designing an overlay network on top of a wireless physical network such that the total signal power required to establish several connection requests is minimized while still providing a good QoS in terms of BER.

3 PROBLEM DEFINITION

Our goal is to develop an energy-efficient routing protocol which guarantees good quality of service in mobile ad-hoc wireless networks. Consider a single connection request between a source node s and a destination node t, and assume that a signal transmission power budget P has been specified for this connection. The basic question to be answered is *how can P be used to instantiate a connection from s to t so that a minimum overall bit error rate is attained?* We shall assume, as in Srinivas and Modiano (2003), that s must merely compute a source route for the connection, and that s has obtained (through the routing protocol) sufficient information about the spatial locations of all local nodes. Furthermore, we assume, as in Li et al. (2003), 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. Even with these simplifying assumptions, the answer to the basic question posed above has many subtle and interesting aspects.

The problem of allocating P to the s-t connection can be approached using either the **traditional scheme** referred to as the *k-hop overlay scheme* or the **general scheme** referred to as the *(N,k) overlay scheme*.

Suppose we use a *k-hop Overlay Scheme*: At the physical level the virtual link from s to t is implemented by a k-hop path (i.e., using $k-1$ uniformly spaced intermediate relay nodes) and $1/k$ of the total power budget P has been assigned to each of these relays (and to s). With this scheme, based on Banerjee and Mirsa (2004), we neglect the power used by the devices to receive the signal, which is assumed to be small compared to the power used during the transmission. Let us denote the bit error rate of such a connection from s to t as $BER(k)$.

Question 1, *Given a fixed power budget P, for what value of k is $BER(k)$ minimum?*

Suppose we now consider a more general *(n,k) Overlay Scheme*: At the physical level the virtual link from s to t is implemented as follows: the source s duplicates the data packets over all n paths to t, and t delivers the first non-corrupt copy of each packet. Note that the mapping of the overlay network onto the physical network need not be one-to-one, so on the physical level, packets need not be traveling on node-disjoint paths—*indeed they may be all traveling along the same path.*

Question 2: *Given a fixed power budget P, what (n, k) overlay will yield a minimal overall bit error rate?*

We will answer these questions here. In particular, we shall see that the answers to these questions depend greatly on the environmental circumstances in which they are asked.

In the next section, the optimal values of n and k were derived analytically in an idealized setting, where the network consists of $k+1$ *equispaced* nodes in one dimension, with the extremal nodes being s and t. Later, we present an algorithm to compute a good choice for n and k in the general (non-equispaced) setting, and we evaluate this algorithm using a series of simulation experiments.

4 THEORETICAL ANALYSIS

The packet error rate over a wireless link is given by

$$PER = 1 - (1 - BER)^L, \tag{1}$$

where L is the packet size in bits and BER is the bit error rate of the channel. For small BER, we can assume a linear approximation, $PER = L \cdot BER$. Minimizing PER is thus attainable by simply minimizing BER; in what follows we restrict our consideration to this objective.

Suppose we have a pair of nodes at distance D communicating using transmitted signal power P over a wireless channel with noise power P_{noise} and antenna/medium constant[2]. The relationship between BER over a wireless channel and the received power P_{rcv} is a function of the modulation scheme. Here we consider a non-coherent binary orthogonal Frequency Shift Keying (FSK) modulation scheme[3] for which the instantaneous channel bit error rate is reported to be

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

by numerous authors including Laurer (1995); Sergey and Gagnon (2004); Proakis (2001). In expression (2), the received power $P_{rcv} = \frac{P}{D^\alpha}$.

The bit error rate of a virtual link implemented by N disjoint paths of length k is given by

$$BER(N, k) = (1 - (1 - BER)^k)^N \tag{3}$$

The total power required for transmissions on the virtual link must exceed $(N(k-1)+1)$ times the transmission power at each relay node (and s). Since each relay must transmit with power at least $P_{rcv}(D/k)^\alpha$, but expression (2) indicates that the received power must be at least $-2P_{noise}\ln(2 \cdot BER)$, it follows that the total transmission power P must be at least

$$-2P_{noise}D^\alpha \frac{((k-1)N+1)}{k^\alpha} \ln(2 \cdot BER). \tag{4}$$

Solving expression (4) for BER and expressing the result in terms of the *channel quality*

$$\gamma = \frac{P}{P_{noise}D^\alpha} \tag{5}$$

we get that

$$BER = \frac{1}{2} e^{-\frac{\gamma}{2}\frac{k^\alpha}{((k-1)N+1)}}. \tag{6}$$

Finally, combining this with expression (3), we get that

$$BER(N, k) = (1 - (1 - \frac{1}{2} e^{-\frac{\gamma}{2}\frac{k^\alpha}{((k-1)N+1)}})^k)^N \tag{7}$$

The results that follow are all based on numerical analysis of expression (7), and address Questions 1 and 2 introduced in Section III. Before beginning the numerical analysis, we determine the real-world ranges of our study parameters:

- α, the medium/antennae constant, is taken to be 2.
- D, the distance between adjacent hops is taken to be $10 - 200$ meters, commensurate with technologies such as WaveLAN and Bluetooth device transceivers—see Wavelan (1999) and Bluetooth (2000) for details.
- P_{min}, the minimum power receivable by a wireless device at the maximum transmission range, and is taken to be from -100dBm to 70dBm (or 10^{-10} to 10^{-7} Watts). For example, P_{min} is $3.65 \cdot 10^{-10}$ Watts for WaveLAN cards, and around -70 dBm for Bluetooth transceivers—see Wavelan (1999) and Bluetooth (2000) for details.
- SNR, the Signal to Noise Ratio which ranges from 0.11 dB to 25 dBm for wireless channels.
- γ, the channel quality, ranges between 0 and 5; these bounds are based on the bounds on D and the SNR.

Figure 1 shows how the virtual link BER changes as the number of disjoint paths increases from 1 to 20 for small and large values of γ. For small k, BER decreases monotonically as the number of alternate paths increases. For large k, however, BER rises until it reaches a local maximum, after which increasing the number of disjoint paths improves the overall BER. Comparing the *heights* of the curves in the bottom chart, we conclude that when the channel conditions are poor (low values of γ), shorter paths result in better overall BER. By considering the *intersections* of the curves in top chart, we see that for $k \geq 2$ hops, virtual links with longer path lengths achieve better BER than those with shorter path lengths.

The analysis of Figure 1 naturally leads one to introduce a concept of a critical density $N_{(k,\gamma)}$: the minimum number of disjoint paths (having k hops each) that have to be established between nodes s and t, so that a better BER is achieved than with a single k-hop path with the same power budget. The next graph (figure 2) illustrates *critical density* as a function of k under various values of γ.

From Figure 2, we see that (i) for any fixed γ the critical density increases exponentially with the number of intermediate hops per path; (ii) for fixed k, critical density grows superlinearly with respect to γ.

Figure 3 shows how the optimal k depends on the values of γ. Considering the top chart, we conclude that for small γ, the BER increases as the number of intermediate hops per path increases. Comparing the *heights* of the curves in the top chart, we conclude that for poor wireless channel conditions, increasing the number of disjoint paths between pairs of source and destination nodes results in better BER.

In case of better wireless channel conditions, however, the bottom chart of figure 3 shows that BER initially increases with k (to a local maximum) and then eventually decreases. When k is small, virtual links with a large number of disjoint paths outperform those with fewer disjoint paths, but this ranking reverses for large k. This could be explained with the fact that, for short paths and large budget power, the quality of wireless channels between neighboring nodes is still good and therefore

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[2] α is typically around 2 for short distances and omnidirectional antennae, and around 4 for longer distances.

[3] Other modulation schemes can be analyzed in similar way, though closed-form analysis may not always be possible.

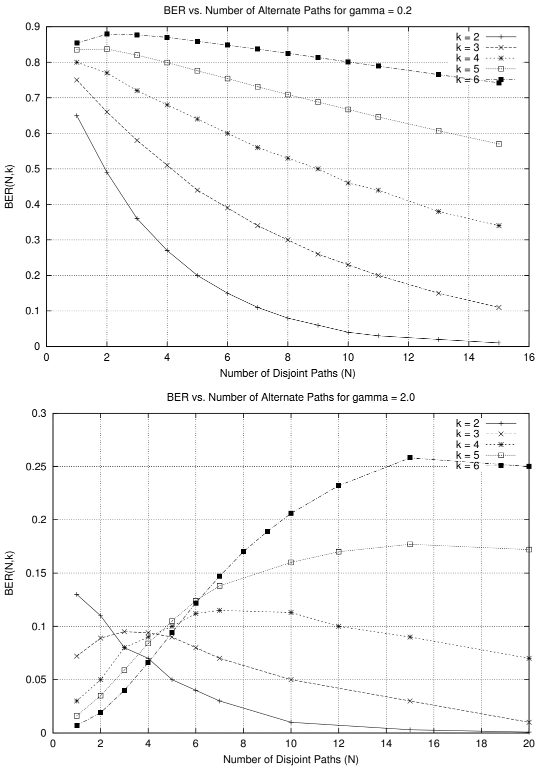

Figure 1: BER vs. duplication

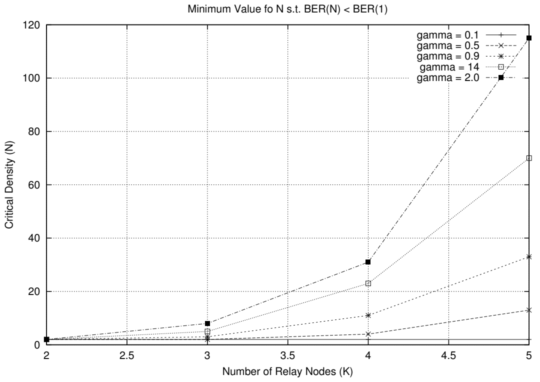

Figure 2: Critical density vs. path length

we can tolerate less power to be consumed. This power saving will be used in establishing additional alternate paths, which will compensate for the degradation of the wireless channels and result to a better virtual link BER. However, as the path length increases, the channel quality between neighboring nodes becomes mediocre. This would favor virtual links with fewer number of alternate paths over those with larger number of alternate paths, while maintaining the same power budget.

In figures 4 and 5 we show how the virtual link BER changes as γ varies between 0.1 and 2 for different number of disjoint paths. Comparing the *heights* of all curves in each chart, we conclude that for low values of γ, better BER is obtained for short paths. However as γ increases, longer paths outperform shorter paths. This could be justified with the fact that, dividing the total power budget between all nodes, still, results in low BER wireless channels quality between adjacent nodes, which favors multi-hop transmission over the direct transmission.

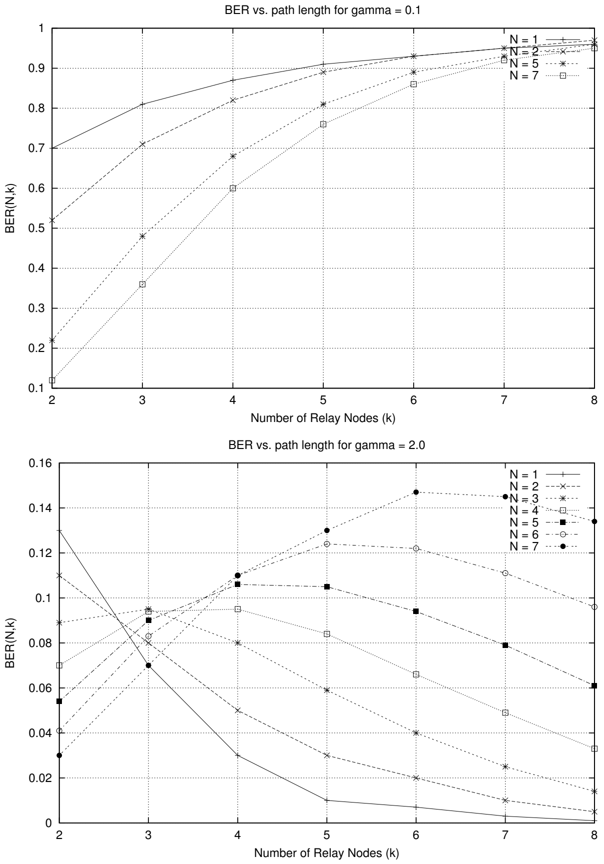

Figure 3: BER vs. path length

The chart in Figure 4 presents a turnover point γ_t (around 0.5), such that, for $\gamma < \gamma_t$, shorter paths outperform longer ones. However, for $\gamma > \gamma_t$, longer paths achieve better BER. Comparing the turnover points of figures 4 and 5, we conclude that, as N increases, γ_t is shifted to the right, indicating that the range of γ, where shorter paths outperform longer ones has increased.

The following three assertions summarize the numerical results we have presented so far.

Assertion 1. *If* $\gamma \ll 1$*, then* $\forall k > k'$,

$$BER(k) > BER(k').$$

Assertion 2. *If* $\gamma \gg 1$*, then* $\exists k_\gamma$ *s.t.* $\forall k > k' \geqslant k_\gamma$,

$$BER(k) < BER(k') \leqslant BER(1).$$

Assertion 3. $\forall k \; \exists N_{(k,\gamma)}$*, such that* $\forall N > N' \geqslant N_{(k,\gamma)}$

$$BER(N,k) < BER(N',k) \leqslant BER(1,k).$$

Assertions 1, 2, and 3 are indeed mathematical theorems, and their proofs are immediate from formal asymptotic analysis of expression (7). Assertion 1 (and 2) follow from ($k \to \infty$) asymptotic analysis when $N = 1$ and $\gamma \approx 0$ (resp. $\gamma \geqslant 2$). Assertion 3 follows from ($N \to \infty$) asymptotic analysis of the same expression for any constant k and γ. Rather than exposit the formal proofs here, we have chosen to present illustrative numerical studies and interpret the nature of the tradeoffs between the total transmission power and virtual link bit error rate–and explain how these tradeoffs are influenced by the channel quality γ. Let us now consider their implications.

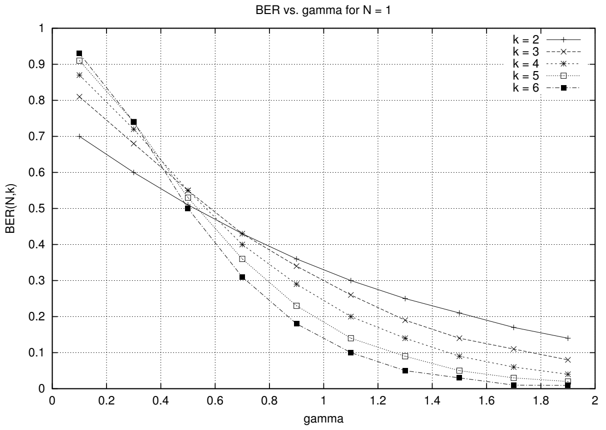

Figure 4: BER vs. γ for 1 multi-hop path

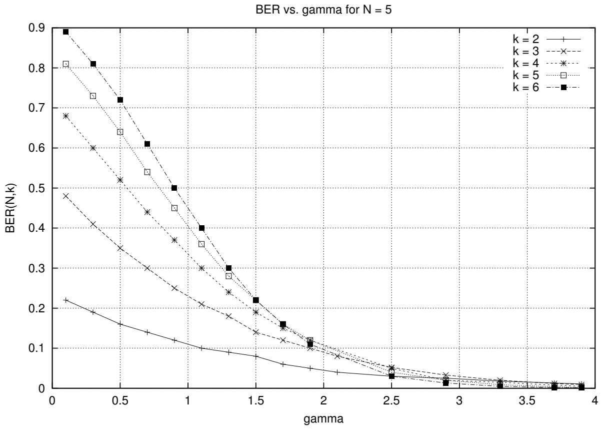

Figure 5: BER vs. γ for 5 multi-hop paths

Assertions 1 and 2 indicate that the optimal value of k depends on a situational parameter we refer to as the *channel quality* γ whose value is proportional to $\frac{P}{D^\alpha}$ (where $\alpha \geqslant 2$ is a constant pertaining to transmission medium and antenna design). They give opposing design guidelines depending on the range of γ: when γ is small, the optimal BER is attained by *minimizing k*, but when γ is large, the optimal BER is attained by *maximizing k*.

Consider the implications of Assertion 2 (when γ is large). As each relay node transmits with power P/k, the downstream neighbor D/k meters away receives the transmission with power $\frac{Pk^{\alpha-1}}{D^\alpha}$. Since a wireless node can receive a transmission only if the power on reception exceeds a threshold minimum power sensitivity $P_{min} > 0$, there exists k_{min} such that for all $k \geqslant k_{min}$, $P_{rcv}(k) \geqslant P_{min}$. Thus one can achieve arbitrarily low BER while maintaining the same power budget, by simply using ever larger numbers of relay nodes.

Assertion 3 states that, in principle, it is always possible to reduce BER by considering a sufficiently large number of node-disjoint paths. The reader will note that for any fixed k and γ, if $N \to \infty$, then $BER(N,k) \to 0$. Unfortunately, in practice, it is not possible to achieve an arbitrarily low BER through the establishment of ever larger numbers of parallel node-disjoint paths. To see why, recall that each relay node transmits with signal power $P/(N(k-1)+1)$ Watts, so the downstream neighbor D/k meters away receives the transmission with power

$$P_{rcv}(N,k) = \frac{Pk^{\alpha-1}}{(N(k-1)+1)D^\alpha}. \tag{8}$$

It follows that for N sufficiently large, $P_{rcv} < P_{min}$, rendering the scheme infeasible: Unfortunately, $P_{min} > 0$ implies that BER cannot be reduced indefinitely while maintaining the same total power budget by using parallel node disjoint paths.

5 THE (n,k) ALGORITHM

In this section, we describe an algorithm, which determines good values for n and k in the general, non-equispaced setting. Suppose at the source node s, we need to send a data packet to a destination node t under the power budget constraint P. Since the (n,k) overlay scheme consists of n node-disjoint paths $p_1, \ldots, p_n$ between s and t, each having length k, to minimize overall BER of the overlay, each of the n paths should itself exhibit a minimal BER. To see this, suppose that one of the n paths p_i is not a minimal BER path; then substituting a path p'_i with $BER(p'_i) < BER(p_i)$ would yield lower BER for the overlay network, since the BER of the overlay is $\prod_{i=1}^{n} BER(p_i)$. It follows that the overlay network maps onto the physical layer as a set of k hop paths between s and t, each having minimal BER. Without other objectives to consider, the algorithm may safely opt to map all n paths in the overlay network onto the same minimal BER path of length k at the physical level. We determine the best value for k (the length of the connection in terms of hops) and n (the number of duplicate packets to be sent over this connection) using the algorithm depicted in the flowchart in Figure 6. The core of the algorithm is a subprocedure which computes the minimal BER path of length exactly k. To achieve this, each node v in the graph data structure (at s) maintains an array of paths, indexed by path length. At any point in the algorithm's execution, the array entry $v.path[\ell]$ holds the minimum weight path of length ℓ from s to v that has been found so far (and $v.path[\ell]$ is said to be "empty" if no path of length ℓ has been found so far). Given a path p, the weight of p is denoted $w(p)$, and is defined to be the sum of the weights on of the edges which comprise it. The last node in p is denoted $tail(p)$. The algorithm maintains a set of candidate paths $\mathcal{P}$, ordered by their weights. Initially $\mathcal{P}$ consists of just the zero-length path which starts and ends at s.

It is not difficult to show that the algorithm below outputs the minimal weight path (and hence by Assertion 1, the minimal BER path) between s and t having exactly k hops. The running time of the algorithm is no more than k times the running time for Dijkstra's algorithm: $O(k|E|\log|V|)$.

```
$\mathcal{P} = \{(s)\}$
for each $p$ in $P$ do
  Remove the path $p$ from $\mathcal{P}$ for which $w(p)$ is minimal.
  for all neighbors $v$ of $tail(p)$ do
    if $v.path[1 + len(p)]$ is empty OR
    $w(p) + w_{tail(p),v} < w(v.path[1 + len(p)])$ then
      Let $p'$ be the path $p$ concatenated with $(tail(p), v)$.
      Set $v.path[1 + len(p)]$ to $p'$.
      Add $p'$ to $\mathcal{P}$.
      if every path in $\mathcal{P}$ has length $> k$ then
        Output the path $t.path[k]$. Stop.
      end if
    end if
  end for
end for
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6 EXPERIMENTAL SETUP

In our simulations, we consider both small and large networks of N wireless nodes distributed into $100m$ x $100m$ square area uniformly at random. Two nodes are connected if and only if

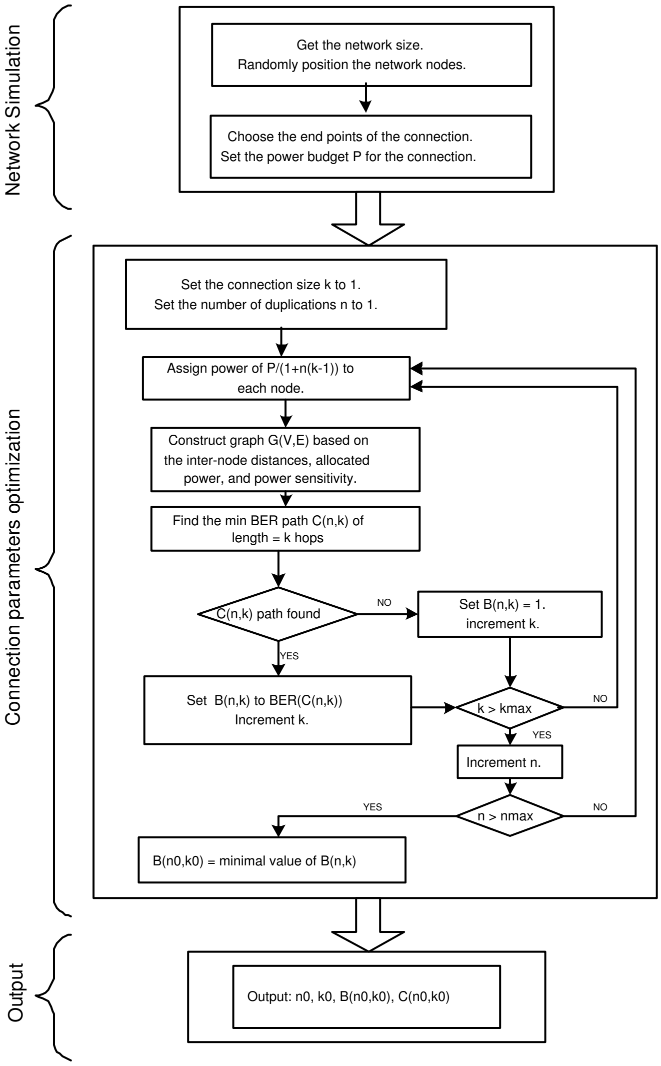

Figure 6: The (n, k) algorithm

the received signal power at one exceeds a uniform node power sensitivity P_{min}. We study the routing decision by considering connection requests between source and destination nodes that are at spatially extremal points of the random network. During the experiment, the network size is kept between 2 to 20 nodes for sparse networks and between 20 to 100+ nodes for dense network. The connection power budget is kept in the range of 200dB for small connection power budget to 3000 dB for large connection power budget.

In experiments where network size was a parameter, networks were "grown" incrementally by adding nodes as N increased. The graphs in the the next section depict average values collected from 2000 trial runs of each experiment scenario.

7 SIMULATION RESULTS

Low Power Budgets. When power budgets are low (less than 250), the (n, k) algorithm's actions coincide with the traditional scheme: packet duplication does not occur. Figure 7 shows that node density influences BER positively in scenarios when power budgets are low. For example, when the power budget $P = 100$, node density influences BER in the range $N = 2$ to $N = 10$. For high power budgets, the influence of node density trails off more rapidly. For example, when $P = 250$, node density ceases to influence BER once $N > 5$. This phenomenon is best explained by the fact that in high density environments, there is increased availability of multi-hop paths which have lower power requirements for end-to-end connectivity. The presence of such low-power multi-hop paths are more significant when the power budget is low. This explanation is confirmed in Figure 8 which illustrates that the routing scheme favors longer paths (i.e. with more hops) when given smaller power budgets. As the power budget is increased, shorter paths (i.e. with fewer hops) are selected. The effect is more pronounced in dense networks since they exhibit greater availability of multi-hop paths with low power requirements. Figure 9 illustrates the same information as Figure 7 but from a different perspective. Dense networks witness a sharper decline in BER when the power budget is increased.

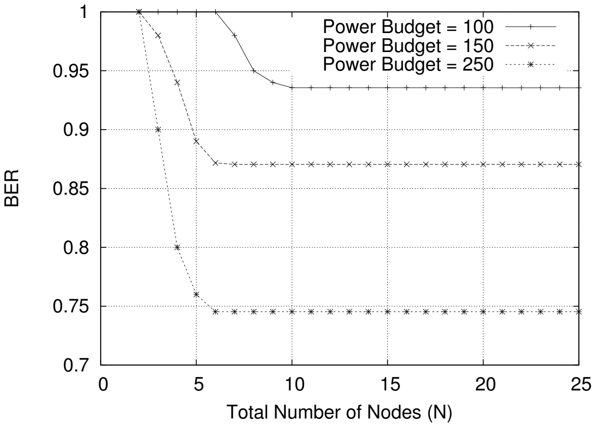

Figure 7: BER vs. N

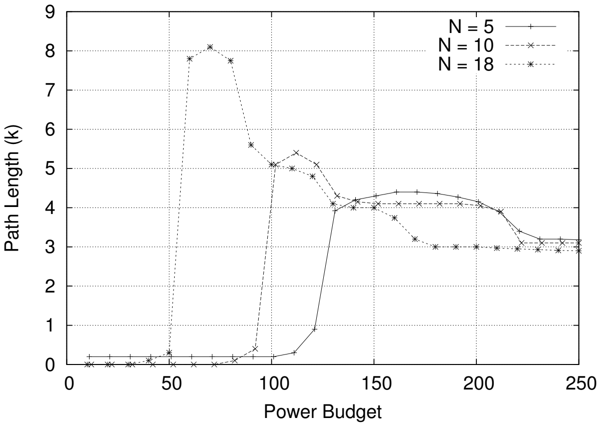

Figure 8: Path Length vs. Power Budget

High Power Budgets. When power budgets are high (greater than 250), the (n, k) algorithm's actions diverge from the traditional scheme: packet duplication occurs. Figures 10 and 11 illustrate the correlation between packet duplications and the improvement of overall bit error rate in sparse networks with high power budgets. Figure 11 shows that the number of duplications increases linearly with the total power budget. For instance, with a network size of 20 nodes, as the total power budget increases from 1500 to 2000, the number of duplications increases by 3; the same increase is observed when we raise the power budget from 2000 to 2500.

The impact of packet replication is seen in Figure 10 which shows that the algorithm achieves a superior bit error rate

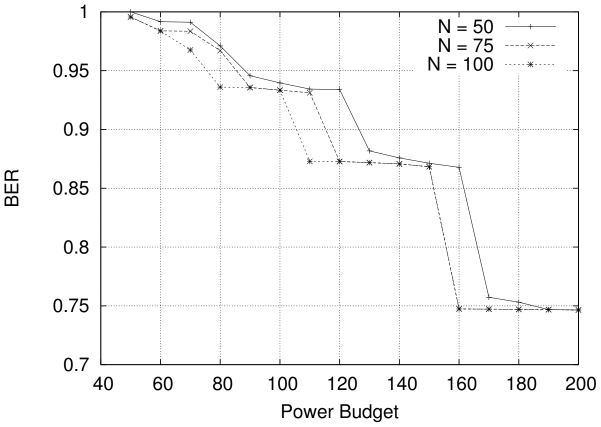

Figure 9: BER vs. Power Budget

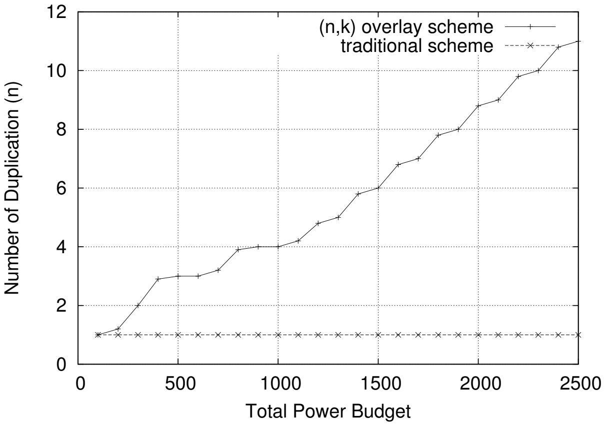

Figure 11: Duplications vs. Power Budget

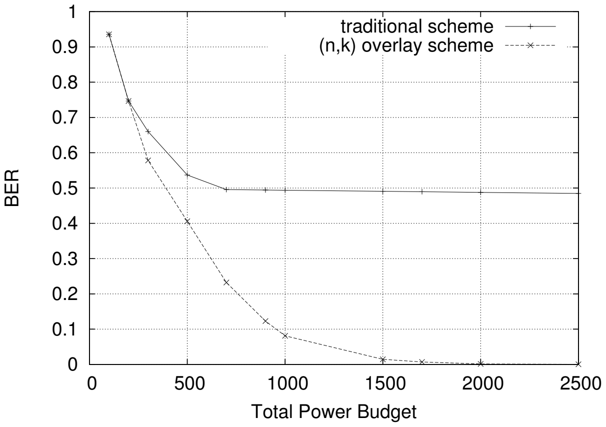

Figure 10: BER vs. Power Budget

by using the increasing power budget to harness the power of packet duplication. Figure 10 shows the geometric nature of the improvement: when the total power budget is raised from 250 to 500, it yields approximately 30% reduction in the BER. Likewise, when total power is raised from 1000 to 1250, we get another reduction of approximately 30% in the BER. In comparing the traditional scheme with the (n, k) overlay scheme we see that the latter reduces BER exponentially faster as the power budget is increased: *It pays to use the power budget to duplicate packets instead of simply allocating more power to nodes along the min-BER path for the transmission of a single packet.*

8 CONCLUSION

In power-limited wireless ad-hoc networks, battery power is an important consideration to take into account while establishing connections. In this paper, we proposed new energy-efficient techniques to lower the packet-level error rates of application layer connections. Our scheme consists of designing an overlay network on top of the physical network. We consider the case of traditional single multi-hop path overlay and the (n, k) overlay scheme.

The (n, k) scheme presented tolerates moderately high BER at the physical layer by successfully compensating for it via packet duplication. The (n, k) scheme significantly outperforms the traditional scheme in terms of BER, when the two approaches are compared under identical (albeit large) power budget constraints. Because individual packet transmissions take place at lower power, systems which utilize the (n, k) overlay scheme can be expected to exhibit lower cross-node interference and enjoy lower bit error rates than traditional systems with identical power budget constraints.

Our numerical analysis show that, for the traditional overlay scheme, minimizing the number of intermediate hops results in better BER when operating in poor wireless channel settings. When wireless channel conditions ameliorate, however, better BER is achieved by maximizing the number of intermediate hops. Another interesting result is that, in several scenarios, the proposed (n, k) overlay scheme outperforms the single multi-hop path scheme under the same total energy budget constraint. Our simulation results show that With low power budgets, duplication does not occur, and longer (hopwise) paths are used (which tend to be more prevalent in denser networks). With higher power budgets, the algorithm favors increasing packet duplication on short (min-hop, min-BER) paths, and significantly outperforms the traditional scheme in terms of BER.

Energy efficient routing has always been a central research topic in wireless network. Most of the prior work has focused on developing routing schemes with the objective of minimizing the total transmission power. We propose using the current results describing the tradeoffs between most parameters involved in the wireless system in the next step of this project, which consists of designing energy-efficient QoS-based routing protocols in mobile ad-hoc wireless network, while minimizing the overall connection BER.

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