Budgeting Power: Packet Duplication and Bit Error Rate Reduction in Wireless Ad-hoc Networks

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ABSTRACT

In this paper we present and evaluate a new technique to lower packet-level error rates of application layer connections in wireless ad-hoc networks. In our scheme, data packets submitted at a connection's source are checksummed and replicated, flowing breadth-first across an 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. Specifically in this paper, we consider overlays consisting of multiple parallel multi-hop paths. We provide an algorithm which determines the optimal parameters of the overlay in terms of the number of paths, their lengths, and specific routes. We demonstrate experimentally that the proposed scheme significantly outperforms traditional routing and power allocation approaches in terms of bit error rate, even when the comparison is made under identical power consumption constraints.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design; C.4 [**Computer Systems Organization**]: Performance of Systems

General Terms

Algorithm, Design, Performance

Keywords

Wireless ad-hoc networks, low bit error rate, energy efficiency, min-hop source routing, power-aware routing.

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. Reconciling the power gap between consumption and supply involves solving the following issues [16]: (i) improving the power efficiency in the system; and (ii) preventing the system deconstruction due to unfair power usage. In our earlier work [4], 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 amount of power to support its instantiation.[1] In this paper, we explore the following salient question:

> Q. If an incoming connection request has been allocated a fixed total power budget to support its instantiation, how should this power budget be utilized to minimize the bit error rate of the connection?

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

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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.

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 then in Section 5 we describe the experimental setup. In Section 6, we describe the algorithm by which minimum BER transmission is acheived within power budget constraints. In Section 7, we present the results of our simulation study by comparing the proposed algorithm against traditional schemes.

2. RELATED WORK

Approaches for efficient power management have been investigated at various protocol layers by several researchers, e.g. see [16, 15, 5]. 1. At the *Physical layer*: Using directional antennae, applying knowledge of spatial neighborhood as a hint in setting transmission power; 2. At the *Datalink 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.

Another category of solutions have been proposed at the network layer, which consists of designing energy aware routing protocols, e.g. see [15, 7, 10]. In wired networks, the emphasis has traditionally been on maximizing end-to-end throughput and minimizing delay. Nonetheless, to maximize the lifetime of mobile hosts, routing algorithms must select the best path from the viewpoint of power constraints and route stability. Hence, routes requiring lower levels of power transmission are preferred, but this can adversely affect end-to-end throughput. Transmission with higher power increases the probability of successful transmission, yielding increased end-to-end throughput. However, high power strategies also result in more cross-node interference, which can destroy existing transmission bands, causing the network to have blocked connections and decreasing effective network capacity.

In [14], Tang and Xue studied the tradeoff between the path lifetime and the total energy in wireless network. 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 approach was based on Srinivas and Modiano's work [13] which presented an efficient source transmit power selection algorithm to find node disjoint paths with minimal total energy requirements.

In [6, 3], Banerjee and Misra argued that energy-aware routing algorithms that are solely based on the energy spent in a single transmission is 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.

Our prior work [4] was a natural extension of Misra [3] and Banerjee [6], reframed by normalizing experiments using fixed power budgets for connections. In that paper, we presented theoretical closed-form results obtained by considering an idealized scenario in which the network consists of k nodes that are uniformly distributed along one dimension. This paper extends these results experimentally, and provides compelling evidence that the theoretical conclusions of [4] continue to hold empirically in realistic randomly generated two dimensional scenarios.

3. PROBLEM DEFINITION

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 (like [13]) 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 (like [13] and [9]) 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 in many ways. In the **traditional scheme** the connection is established using the shortest (min-hop) path from s to t for which the cumulative hop-by-hop power requirements do not exceed P. As the authors argued in [4], the traditional scheme is merely a very special case of a general **overlay scheme**. In the general framework, each application-layer connection is implemented at the physical level by an overlay network: data packets submitted at the connection source are checksummed and duplicated, flowing breadth-first across the overlay network towards the destination. Each node delivers/forwards all error-free copies of each packet, in arrival-order, dropping any packets that are corrupt or duplicate. Each node in the overlay network is assigned a suitable fraction of the total power budget (e.g. in proportion to the distance to downstream neighbors), so that the total power allocated to the transmission of a packet across the overlay is bounded by P.

In our previous work [4], we considered a special case of the general overlay scheme, which we designated the **(n,k) overlay scheme**. The traditional scheme is subsumed by this scheme, since it corresponds to the case when $n = 1$. In the (n, k) scheme each application-layer connection is implemented as an overlay network consisting of n node-disjoint paths between s and t, with each path having length k. For each node in the overlay network, we assign an equal fraction of the total power budget P. Functionally, the overlay network implements a virtual link 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 travelling on node-disjoint paths—indeed they may be all travelling along the same path. In [4], we presumed that the network consisted of $k + 1$ equispaced nodes in one dimension, with the extremal nodes being s and t. The optimal values of n and k were derived analytically in this idealized setting. In contrast, in this paper we report on randomly generated realistic experimental scenarios and provide an algorithm to determine the optimal values of n and k and the associated overlay network implementing the connection. The question [Q] posed in Section 1 then becomes: *Given a fixed power budget P, what (n, k) overlay will yield a minimal overall bit error rate?* We will answer this question here.

4. NETWORK MODEL

We consider a wireless ad-hoc network consisting of N nodes equipped with omni-directional antennas that can dynamically adjust their transmition power. We model this network as a 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 [6] and [14]. 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 [6]). In order to correctly decode the signal at the receiver side, it is required that

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

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 $P_{min}(i)$.

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 [6].

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

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 Queying (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 [11, 12, 8] to be:

$$BER = 0.5 \, e^{-\frac{P_{\text{rcv}}}{2 P_{\text{noise}}}} \tag{5}$$

Let ρ be a *connection request* defined by a source node s and a target node t. We will assign to each edge (i, j) a cost $w_{i,j}$ = -log$(1 - BER(i, j))$, where $1 - BER(i, j)$ denotes the probability that a packet will, successfully be transmitted over link (i, j). Such labelling of the edges of the graph makes the minimum cost path have a minimal bit error rate. To see this, note that a path consisting of a sequence of links $L_1, \ldots, L_r$ has a BER equal to

$$1 - \prod_{\ell=1}^{r} 1 - BER(L_\ell). \tag{6}$$

To minimize (6), we maximize $\prod_{\ell=1}^{r} 1 - BER(L_\ell)$, which by monotonicity of log, is equivalent to maximizing $\sum_{\ell=1}^{r} \log(1 - BER(L_\ell))$. Maximizing this is, in turn, equivalent to minimizing $\sum_{\ell=1}^{r} - \log(1 - BER(L_\ell))$. We have shown:

Assertion 1. In a graph where each edge (i, j) has weight $w_{i,j} = -\log(1 - BER(i, j))$, every min-weight path enjoys the property that it attains minimal BER between its endpoints.

5. EXPERIMENTAL SETUP

In our simulations, we consider both small and large networks of N wireless nodes distributed into $100m$ x $100m$ square area uniformally at random. Two nodes are connected if and only if 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 spacially extremal points of the random network. During the experiment, all network parameters involved in the system are kept in the following ranges:

- *Network size*: we consider the case of sparse networks (N ranging from 2 to 20 nodes) and dense networks (N ranging from 20 to 100+ nodes).
- *Connection power budget*: ranging from 200dB for small connection power budget to 3000dB for large connection power budgets.
- α: which is scaling constant is kept at 2 as appropriate to our $100m$ scale.
- P_{min}: which characterizes any wireless device and represents the minimum power receivable by the device at the maximum transmission range is kept in the range 70 down to -100 dB. These ranges were based on WaveLAN [2] and Bluetooth [1] specifications.
- SNR: which is the Signal to Noise Ratio of the wireless channel, ranges form $25dB$ down to $0.11dB$, as appropriate to a typical range of SNR values for wireless channel.

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.

6. THE (N, K) ALGORITHM

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 1. 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.

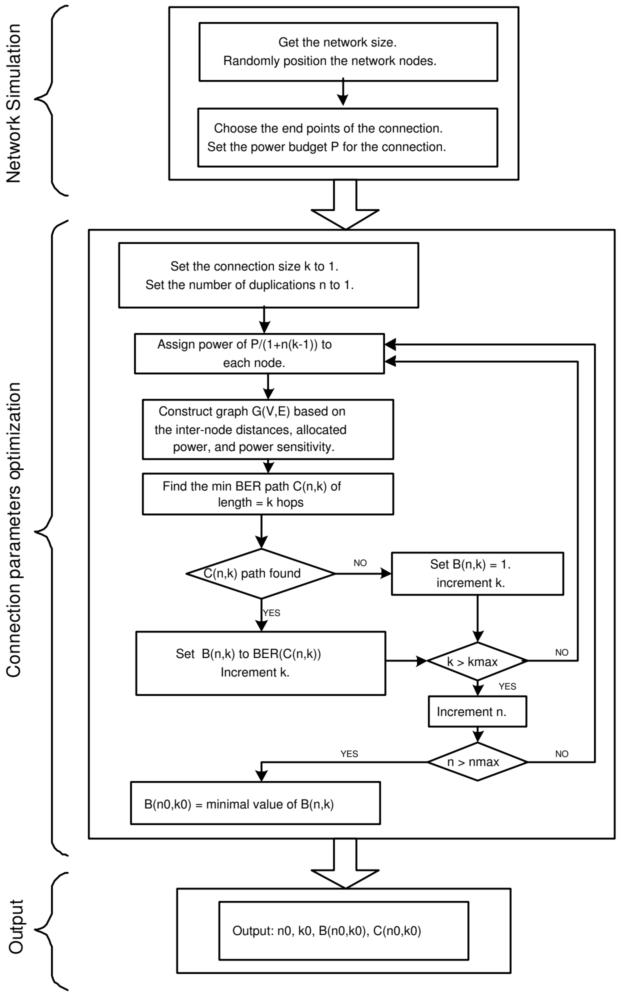

Figure 1: The (n, k) algorithm

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: $O(k|E| \log |V|)$.

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$\mathcal{P} = \{(s)\}$
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
```

7. 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 2 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 3 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 pronouned in dense networks since they exhibit greater availability of multi-hop paths with low power requirements. Figure 4 illustrates the same information as Figure 2 but from a different perspective. Dense networks witness a sharper decline in BER when the power budget is increased.

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 5 and 6 illustrate the correlation between packet duplications and the improvement of overall bit error rate in sparse networks with high power budgets. Figure 6 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.

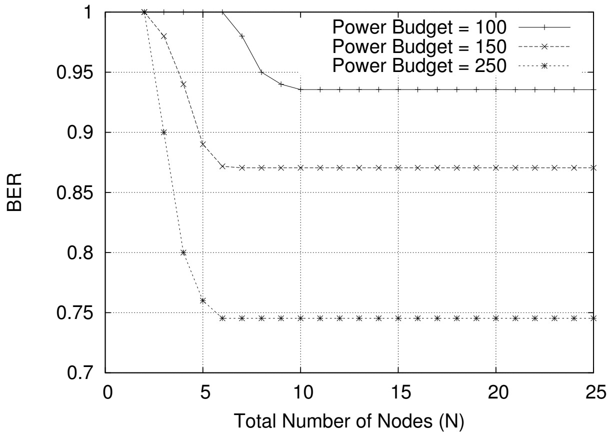

Figure 2: BER vs. N

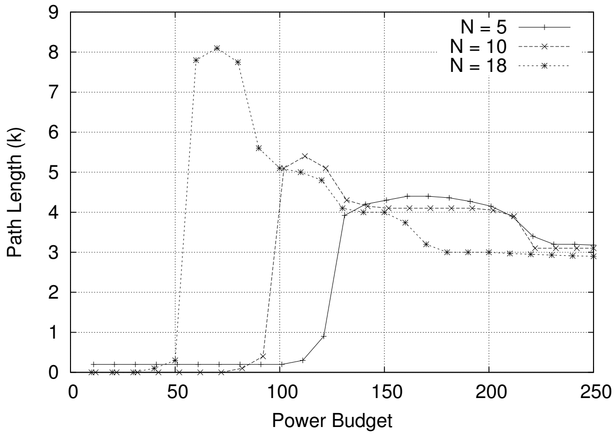

Figure 3: Path Length vs. Power Budget

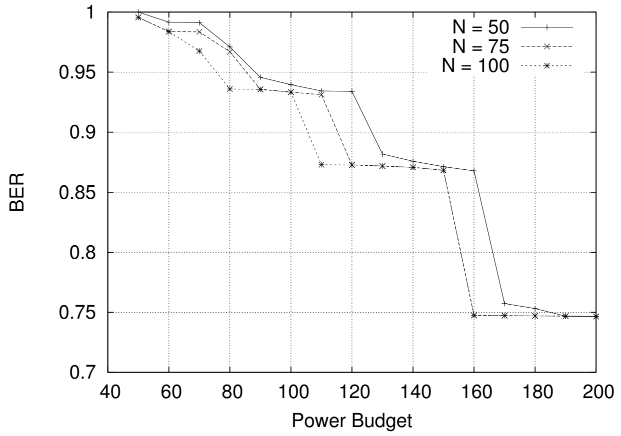

Figure 4: BER vs. Power Budget

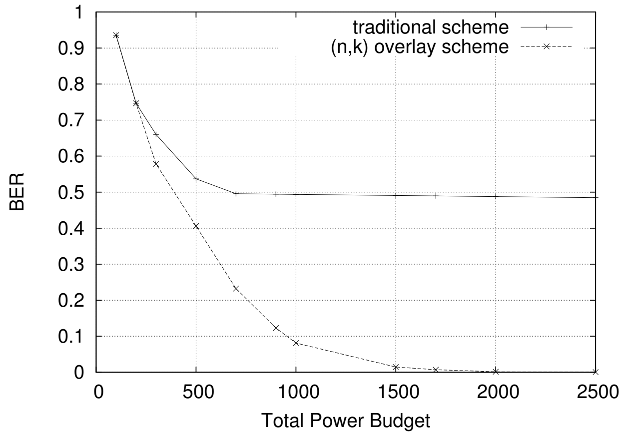

Figure 5: BER vs. Power Budget

The impact of packet replication is seen in Figure 5 which shows that the algorithm achieves a superior bit error rate by using the increasing power budget to harness the power of packet duplication. Figure 5 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

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. Returning to the original question [Q] posed in Section 1, the results of this paper provide the following answer:

Given a specific power budget constraint, the (n, k) algorithm determines optimal values for duplication n, path length k, and the precise path $C(n, k)$. 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.

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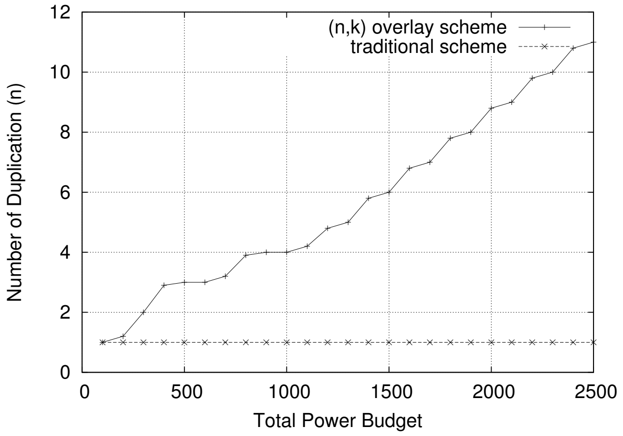

Figure 6: Duplications vs. Power Budget

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