Selection metrics for multihop cooperative relaying

Jonghyun Kim Stephan Bohacek
kim@eecis.udel.edu bohacek@udel.edu

Abstract

Cooperative relaying enables nodes to actively cooperate to deliver packets to their destination. The best-select protocol (BSP) implements a type of cooperative relaying that generalizes single path routing with sets of nodes (relay-sets) replacing the concept of a single node relay. Thus, while in traditional single path routing, packets hop from node to node, in BSP, packets hop from relay-set to relay-set. Through the exchange of channel gain information between relay-sets, the best node within a relay-set is selected to transmit the data packet on behalf of the entire relay-set. The node selected depends on the metric used. Any metric that can be posed in a dynamic programming framework can be used. In this paper, performance gains from a number of selection metrics are investigated. Specific selection metrics include maximizing the probability of packet delivery, maximizing the minimum SNR along the path, maximizing the throughput, minimizing end-to-end delay, minimizing the total power, and minimizing the total energy. It will be shown that BSP can achieve significant gains in all of these metrics, with the possible exception of maximizing the probability of packet delivery. The performance is investigated with several different propagation models and node densities.

1 Introduction

In traditional multihop wireless data networks, route search and packet forwarding are separated; first a route is found, and then packets are forwarded along the route. In the case that multipath routing is employed, the situation is similar, but a set of paths are found, and then, packets are forwarded along each route either probabilistically, or the routes are used as precomputed backups [1]. In any case, nodes act alone to forward the packet to it next hop. In cooperative relaying, a group of nodes act together to forward packets. While several variants of cooperative relaying are possible, one approach is to generalize the single node that forwards the packet to a set of nodes that cooperate (see [2] for an alternative approach). Such a set of nodes is called a relay-set. Thus, while traditional networking forwards packets from node to node, this form of cooperative relaying forwards packets from relay-set to relay-set. Within the relay-set paradigm, there are also many possible approaches. For example, in some cases, a number of nodes transmit the same or different parts of the packet. In such cases, the total transmission power used to transmit the data packet between two relay-sets is distributed among a number of node pairs [3], [4]. However, in [5], it was shown that in the case of two-hop paths, if the channels are known, then the optimal approach is to allocate all power to the best node pair. Such an approach is known as best-select relaying.

Best-select protocol (BSP) is a multihop extension of best-select relaying [6]. Hence, BSP makes active use of channel measurements and attempts to select the best path. A distinguishing feature of BSP is that it is highly dynamic and finds paths on a per packet basis. The path that a packet follows depends on instantaneous and smoothed channel gain measurements. As a result of the highly reactive nature of BSP, BSP achieves long connection lifetimes. Specifically, in [6], it was found that the time between route searches is between 5 and 20 times longer with BSP as compared to least-hop routing. Furthermore, the links used by BSP had a significantly larger SNR than the links used by least-hop routing.

In [6], the ability of BSP to achieve high per link SNR was met by explicitly setting BSP's metric for comparing paths to maximize the SNR. However, a large number of other selection metrics are possible. Indeed, any metric that can be posed in a dynamic programming framework can be used to select paths. On the other hand, it is not clear what kind of gains will be achieved if other metrics are used. In this paper, the performance gains associated with several metrics are explored. Specifically, we investigate the impact of maximizing the probability of packet delivery, maximizing the minimum SNR along the path, maximizing

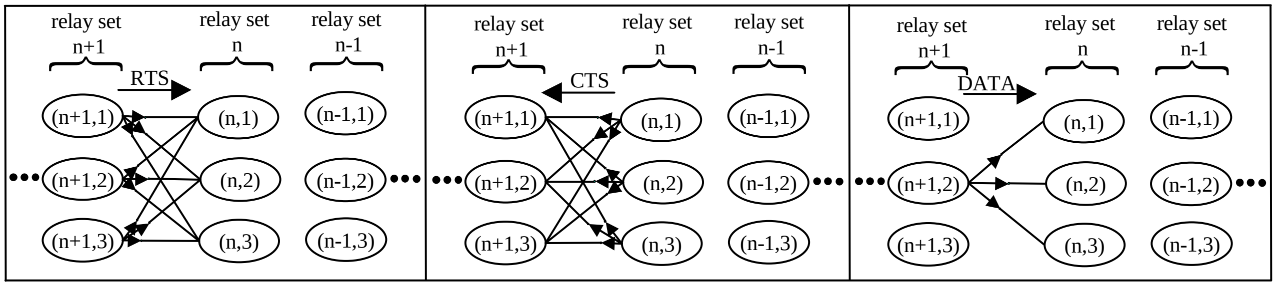

Figure 1. Best-Select Protocol

the throughput, minimizing end-to-end delay, minimizing the total power, and minimizing the total energy. It will be shown that BSP can achieve significant gains in all of these metrics, with the possible exception of maximizing the probability of packet delivery.

This investigation examines these performance gains in several different scenarios. Specifically, we consider an idealized version of BSP where the nodes are uniformly distributed and the channel gains are lognormally distributed, an idealized version of BSP when the nodes are in an urban area, and an QualNet implementation of BSP when nodes are in an urban area. The urban area simulations utilize channel gains from performing ray-tracing on a map of an urban area. Thus, these channel gains are similar to those that would be found in an urban deployment. In each scenario, two different node densities are examined, sparse and dense.

The paper proceeds as follows. In the next section a brief overview of BSP is provided. In Section 3, the methodology for evaluating the performance gains is discussed. Section 4 the different selection metrics are evaluated. Section 5 explores whether different selection metrics gives rise to different paths, or packets follow similar path regardless of the metric. It will be shown that they do not follow the same path. And finally, Section 6 provides a summary of the results and concluding remarks.

2 Best-Select Protocol (BSP)

As mentioned above, BSP groups nodes into relay-sets. The relay-set that is n hops from the destination is referred to as the n-th relay-set. The i-th node within the n-th relay-set is denoted by (n, i). The nodes within the n-th relay-set cooperate with the nodes within the $(n-1)$-th relay-set to determine which node in the n-th relay-set should transmit the data packet. Specifically, the nodes within the n-th relay-set transmit a RTS packet to the nodes in the $(n-1)$-th relay-set. These transmissions occur simultaneously using CDMA with each node using a different code. Each node in the $(n-1)$-th relay-set receives all the RTSs and records the channel gains over each channel. We denote the channel gain from node (n, i) to node $(n-1, j)$ as $R_{(n,i),(n-1,j)}$. Assuming that the channel is idle, all the nodes in the $(n-1)$-th relay-set transmit a CTS simultaneously using CDMA. These CTS packets contain the just measured channel gains along with other channel gain information. Each node in the n-th relay-set receives these CTSs along with the embedded channel gain information. Since all nodes have received the same information, they are able to make the same decision as to which node is best suited to transmit. This node then transmits the data packet using the entire bandwidth. Figure 1 illustrates the approach.

The decision as to which node is best suited to transmit does not only depend the channel gains $R_{(n,i),(n-1,j)}$, but also on the downstream channel gains, $R_{(n-1,j),(n-2,k)}$, $R_{(n-2,k),(n-3,l)}$, etc. This amount of channel gain information cannot be economically included into the CTS packets. Instead, the downstream channel information is encapsulated into a scalar, which we denote as J. Specifically, the relevant downstream channel information from node (n, i) is denoted $J_{(n,i)}$ and depends on the selection metric. For example, if the objective is to maximize the probability of delivering the packet to the destination, then $J_{(n,i)}$ is the probability of delivering the packet from node (n, i) to the destination via the best path from node (n, i). In this paper we explore several different objectives, and hence J will take many different meanings. However, in all cases, it will encapsulate the downstream channel information.

A key requirement for J and the selection metric is that $J_{(n,i)}$ only depends on

$$\left\{J_{(n-1,j)},\ R_{(n,i),(n-1,j)} : (n-1,j) \text{ in the } (n-1)\text{-th relay-set}\right\}.$$

Thus we insist that

$$J_{(n,i)} = \Phi\left(J_{(n-1,1)}, J_{(n-1,2)}, ..., R_{(n,i),(n-1,1)}, R_{(n,i),(n-1,2)}, ...\right), \tag{1}$$

for some function Φ. Note that (1) is the recursive formula used to solve dynamic programming where n denotes the stage, $J_{(n,i)}$ denotes the cost-to-go and the stage cost is a function of $R_{(n,i),(n-1,j)}$ [7]. Indeed, BSP can accommodate any objective that can be framed as dynamic program. Hence, BSP is much like distance vector routing, which also can be viewed as dynamic programming. However, traditional routing is often focused on simple metrics such as the number of hops. While there has been some work toward incorporating metrics that include channel gains, these approaches have met with minimal success since the channel gains vary at far shorter time-scales than traditional routing functions. Hence, BSP allows one to realistically consider metrics that utilize channel gains. Of course other observables such as remaining battery power can also be considered. This paper only focuses on the metrics that use channel gain (and, of course the number of hops).

Several details of BSP are not addressed here and can be found in [6]. Specifically, the construction and maintenance of the relay-sets and use of past channel measurements are likely to have an impact on the performance. However, a careful investigation of these issues is reserved for future work.

3 Methodology

Three different scenarios are used to evaluate the selection metrics. We refer to these as lognormal idealized BSP, urban idealized BSP, and urban implemented BSP, or simply implemented BSP. These scenarios are discussed next.

The lognormal idealized BSP used random node locations and stochastic channel gains. Specifically, nodes are uniformly spread throughout a region and channel gains are lognormally distributed. Specifically, the channel gain in dB is $-27\log_{10}(d) - X$, where d is the distance between the transmitter and receiver and X is a normally distributed random variable with mean 0 and standard deviation of 11.8. The lognormal channel gains are based on the extensively validated lognormal shadowing model [8]. The total area considered is 1.5 km^2. Two node densities are used; the sparse density has 130 nodes/km^2, and dense has 260 nodes/km^2. In this model, no mobility is considered and all channels are assumed to be constant. In this setting, the source and destination are selected at random. The least-hop path between the source and destination is found. The path is restricted to only use links where the channel gain is greater than $-52dB$. If there are multiple least-hop paths, one is selected at random. If there are no paths, then the trial is excluded and a new set of node locations, source, and destination are selected. If a path is found, the performance metric is evaluated for this path.

This shortest path is taken as the initial set of relay-sets. That is, the initial relay-sets have one node and these nodes make up the least-hop path. The relay-sets are then expanded as follows. If a node is able to communicate with at least one node in the $(n+1)$-th relay-set and a node in the $(n-1)$-th relay-set, then the node joins the n-th relay-set. The size of the relay-set is not restricted[1]. The best path is then selected from the nodes that make up the relay-sets. The metric is evaluated over this path.

While the evaluation of the selection metric in such the idealized lognormal scenario provides some insight, it is not particularly realistic. The most serious drawback is that the channel gains are modeled in an unrealistic fashion. In order to model multihop mobile network in a more realistic urban area, a realistic propagation and mobility tool is used. The propagation is based on 3-D ray-tracing that models reflections off of buildings and the ground, transmissions through building walls into, out of, and through buildings, and diffraction around and over buildings [9]. The location of buildings and roads is modeled after the Paddington area of London.

We focus on a simple pedestrian mobility model that mimics the popular random way-point mobility. Specifically, nodes pick an office location in the modeled area and travel to that location. The nodes are

[1] This important topic is left for future work.

restricted to move along sidewalks, enter through doors and move along hallways to offices. Once the node arrives at the desired office, the node picks another office at random and travels to that location. For each trip, the node selects a random desired walking speed. Walking speeds are Gaussian with mean 1.34 m/s and standard deviation 0.26 [10], [11], [12]. The mobility model used in this investigation includes traffic lights and models pedestrian dynamics [13].

Once the channel gains are known, the selection metrics can be investigated. To this end, a source and destination are selected at random, and the least-hop path between these nodes is found. If there exists multiple least-hop paths, one is selected, and if there are no paths, a new source and destination are selected. As described above, this least-hop path is used as a basis to generate relay-sets. The value of the metric is evaluated for the least-hop path and for BSP over the relay-sets generated by this least-hop path. Next, time is increased by one second. As a result the nodes may move. If, the nodes which had composed the least-hop path are still connected the metric is evaluated. In this case, the relay-sets are adjusted if some nodes have drifted such that they cannot communicate with at least one node in the upstream relay-set and one nodes in the downstream relay-set. The value of the metric is evaluated along the adjusted relay-sets. The metrics are repeatedly evaluated until the least-hop path breaks or the simulation ends (300 seconds). (Note, the least-hop path will always break before the BSP path). Since this approach is able to always correctly build the relay-sets and always uses the correct value of the selection metric, we call this an *idealized BSP*. A more realistic case is provided by implementing BSP in a packet simulator described next.

Packet simulation of BSP is performed with QualNet. The details of the BSP implementation is described in [6]. To evaluate the selection metrics, the same connections, mobility, and channel gains used by the urban idealized BSP are used. The implementation of BSP is much like the idealized BSP in the sense that first a least-hop path is found. This path is then enhanced by adding more and more nodes to the relay-sets. However, as mentioned above, the relay-sets grow relatively slowly, adding a few nodes every time a packet is delivered. Furthermore, the idealized BSP assumes that each nodes knows the correct value of the selection metrics. The implementation of BSP exchanges channel information via RTS-CTS exchanges. However, as described in [6], some of the channel information is only an estimate.

It should be emphasized that the in both the urban idealized BSP and urban implementation of BSP, the comparison between the performance of the least-hop path and the path provided by BSP stops once the least-hop path fails. Such a restriction is necessary since a comparison is not possible if one path does not exist. However, this restriction eliminates situations where BSP provides a far better path than the least-hop path. Since these situations are eliminated, the performance evaluation is skewed toward situations where the least-hop path performs well. Nonetheless, we separate the performance comparison of BSP to least-hop in terms of the selection metric from the comparison in terms of path lifetime. The comparison of BSP to least-hop in terms of path lifetime was addressed in [6] where it was shown that BSP leads to path lifetimes that are 5-20 times longer than least-hop paths.

4 Selection Metrics

Like routing metrics, cooperative networking allows the selection of links according to different metrics. However, the highly dynamic nature of cooperative relaying allows new metrics to be explored. To see this, consider signal to noise ratio (SNR). While it is possible to use SNR when selecting a path, it has been shown to only be a marginal predictor of the quality of the path [14]. The reason for this is that the SNR may rapidly vary and is difficult to predict, especially on the time-scales relevant for routing.

On the other hand, BSP is able to quickly adjust the way in which packets are delivered. Specifically, the exact path a packet takes is determined only as the packet is being sent through the network. Thus, BSP is able to react quickly to changes in the channel gains. The question addressed by this paper is which metrics can be use to select the node within the relay-set to transmit and what is the impact of using best-select with these metrics.

4.1 Maximizing delivery probability given fixed transmission power

It is well known that wireless transmissions are subject to transmission errors. If TCP or some other reliable layer protocol is used, a link layer transmission error will result in a transport layer retransmission. As a result, the same packet will traverse the same set of links twice, wasting network resources. To avoid

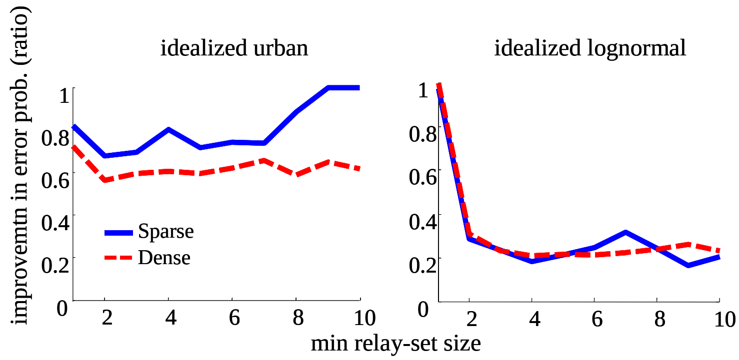

Figure 2. Error probability. The average ratio of the probability of successful packet delivery with BSP to the probability of successful packet delivery with least-hop routing.

transmission error and its associated inefficiency, the received signal strength and hence, the probability of successful transmission can be increased by increasing the transmission power. However, such an approach may exasperate interference and drain mobile node's batteries. Thus, we consider the problem of maximizing the probability that the packet will be delivered to the destination with the constraint that the transmission power is fixed.

To this end the following notation is required. Let $f(V)$ be the probability of transmission error when the SNR is V, and let $J_{(n,i)}$ be the probability of successfully delivering the packet to the destination from node (n,i). Furthermore, let $R_{(n,i),(n-1,j)}$ be the channel gain from node (n,i) to $(n-1,j)$. Let I_n be an ordering of the nodes in the n-th relay-set such that $J_{(n,I_n(1))} \geq J_{(n,I_n(2))} \geq \cdots$. Then J obeys

$$
\begin{aligned}
J_{(n,i)} \quad = \quad & f\left(R_{(n,i),(n-1,I(1))}X\right) \times J_{(n-1,I_{n-1}(1))} \\
& + \left(1 - f\left(R_{(n,i),(n-1,I_{n-1}(1))}X\right)\right) \times f\left(R_{(n,i),(n-1,I_{n-1}(2))}X\right) \times J_{(n-1,I_{n-1}(2))} \\
& + \cdots
\end{aligned}
$$

where X is the transmission power. To understand this equation, note that the first term is the probability of successfully transmitting from node (n,i) to node $(n-1, I_{n-1}(1))$ and then successfully delivering the packet from node $(n-1, I_{n-1}(1))$ to the destination. The second term is the probability of failing to successfully transmit to $(n-1, I_{n-1}(1))$, but succeeding to deliver the packet via $(n-1, I_{n-1}(2))$. The rest of the terms are similar.

As discussed above, node (n,i) can determine $J_{(n,i)}$ by collecting the channel gain measurements and $J_{(n-1,j)}$ from the CTS packets. Furthermore, all nodes in the n-th relay-set collect all channel gains $R_{(n,i),(n-1,j)}$ and $J_{(n-1,j)}$ for all i and j. Thus, all nodes in the relay-set can compute $J_{(n,i)}$ for all i. That is, every node in the n-th relay set can determine which node has the largest probability of successful delivery of the packet to the destination., i.e., which node has the largest $J_{(n,i)}$. Thus, the nodes with the largest $J_{(n,i)}$ can transmit while the other nodes in the relay-set remain silent.

Note that $J_{(n,1)}$ is the probability that the transmission from the source will lead to a successful delivery of the packet. Hence, this selection metric can be evaluated by examining $J_{(n,1)}$.

Figure 2 shows the performance of this metric for the lognormal idealized BSP and the urban idealized BSP. These plots show the ratio of the probability of failing to deliver the packet (i.e., $1 - J_{(n,1)}$) using BSP to the probability failing when using traditional least-hop single path routing. We make this comparison as a function of the size of the smallest relay-set. We have found that the size of the smallest relay-set is tightly correlated to the performance of BSP.

Figure 2 shows that the ratio is often less than one, indicating that BSP results in a lower probability of failure than least-hop single path routing. However, the difference is not particularly impressive. Moreover, the variance is quite large. The reason for the marginal performance is that there is a small range to SNRs that lead to transmission probabilities that are not either very close to zero or very close to one. Thus, either both methods provide low error probability or the least-hop path breaks, which ends the comparison. Due to this poor performance, this metric has not implemented in the QualNet implementation of BSP.

4.2 Maximizing the minimum SNR along the path

It is well known that the probability of transmission error is strongly related to the SNR. Thus, a large SNR allows for a low transmission error, lower transmission power, and/or higher data rate. Here the selection metric finds the path that has the largest minimum SNR. That is, for each hop along the path, the SNR is evaluated. The quality of the path is taken to be the smallest SNR along the path. The link with the smallest SNR can be thought of as the bottleneck of the path. Hence, we seek to best bottleneck.

Define $J_{(n,i)}$ to be the minimum SNR over the best path from node (n, i) to the destination. Then the following holds

$$J_{(n,i)} = \max_{j} \left(\min\left(R_{(n,i),(n-1,j)}, J_{(n-1,j)}\right),\right), \tag{2}$$

where the maximization is over all nodes in the $(n-1)$-th relay-set. Note that the minimization is between the SNR from node (n, i) to $(n-1, j)$ and the minimum SNR from node $(n-1, j)$ to the destination. Thus, the minimum SNR from node (n, i) to the destination via node $(n-1, j)$ is $\min\left(R_{(n,i).(n-1,j)}, J_{(n-1,j)}\right)$.

In order to evaluate this metric we can simply examine $J_{(n,1)}$. Indeed, this is done when evaluating the metric in the case of idealized BSP. However, in the implementation of BSP, it is more difficult to determine the resulting value of the minimum SNR experienced. To understand this, suppose that j^* achieves the maximum in (2). Then, if node (n, i) is selected to transmit the packet, it intends to transmit to node $(n-1, j^*)$. In this case, BSP is expecting the packet to traverse a link with SNR of $R_{(n,i)(n-1,j^*)}$. After this, BSP expects that the packet will experience an SNR of $J_{(n-1,j^*)}$. However, in reality, the transmission from (n, i) will likely reach other nodes such as $(n-1, j^+)$, where $j^* \neq j^+$. Furthermore, it is possible that $J_{(n-1,j^*)} < J_{(n-1,j^+)}$. That is, while BSP only expected the packet to reach $(n-1, j^*)$ and hence, experience a remaining SNR of $J_{(n-1,j^*)}$, the packet reached node $(n-1, j^+)$ and must now only experience a remaining SNR of $J_{(n-1,j^+)}$. To accommodate such cases, when evaluating the implementation of BSP, we evaluate the selection metric by taking the minimum value of $R_{(n,i),(n-1,j^*)}$. That is, we consider the smallest SNR over a link that BSP intends on sending the packet. Note that this will result in the minimum SNR to be larger than the SNR that BSP expects.

Note that the reason for that J does not accurately reflect the performance is that the (2) does not account for the probabilistic nature of the transmissions. Below some metrics that do account for the probabilistic nature of transmission are investigated.

The performance of this selection metric is shown in Figure 3. In general, BSP is able to provide significantly higher minimum SNR than the least-hop routing. For example, two orders of magnitude improvement is not uncommon for the idealized and implemented urban cases. Figure 3 also shows a smaller, but still significant improvement in the idealized lognormal shadowing case. One reason that the improvement in the lognormal case is smaller than the other cases is that the lognormal case does not consider node mobility. In the case that nodes *do* move, the original least-hops path may perform quite poorly as some links are stretched to the point where communication is only just barely possible. However, the mobility has much less impact on BSP. Specifically, BSP dynamically adjusts the path and can achieve far higher SNR. As a result, BSP leads to drastic improvements in performance when nodes are mobile.

It can be noticed in Figure 3 the implemented urban case shows more improvement than the idealized case. This difference is especially noticeable for small relay-set size. As discussed above, the reason for this is that (2) does not account for the probabilistic nature of packet transmission.

4.3 Maximizing throughput subject to a transmission error probability constraint

Perhaps the most widely examined metric in networking is throughput. Here we say that the throughput of a connection is the minimum bit-rate along a path, i.e., the bit-rate of the bottleneck link. Of course, it is always possible to transmit at a very high bit-rate, however, a high bit-rate may lead to a high transmission error probability. Thus, we consider only bit-rates that meet a specified link transmission error probability constraint. Like the max-min SNR above, BSP will search for the path whose minimum bit-rate is maximized where each link bit-rate is maximized over all bit-rates that meet the transmission error constraint.

To this end, define $J_{(n,i)}$ to be the throughput from node (n, i) to the destination. Then

$$J_{(n,i)} = \max_{(n-1,j)} \max_{\left\{B: f\left(R_{(n,i),(n-1,j)}X, B\right) \geq \texttt{PROB\_THRESH}\right\}} \min\left(B, J_{(n-1,j)}\right), \tag{3}$$

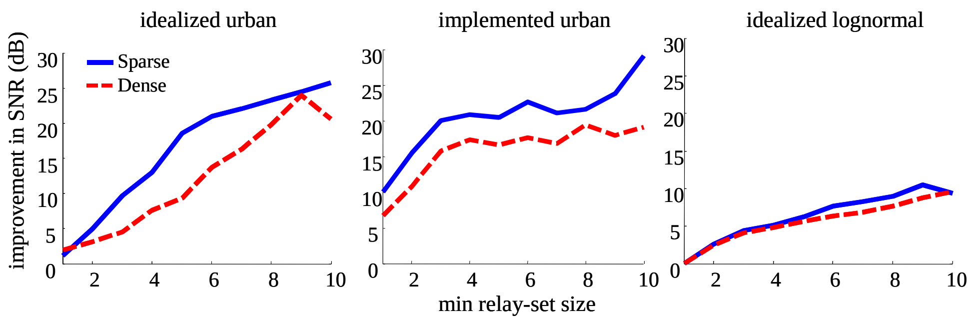

Figure 3. Max-Min SNR. The average ratio of the minimum SNR along the path with BSP to the minimum SNR along the path with least-hop routing.

where $f\left(R_{(n,i),(n-1,j)}X, B\right)$ is the probability of successful transmission at bit-rate B and SNR $R_{(n,i),(n-1,j)}X$ where X is the transmission power; the outer maximization is over all nodes $(n-1,j)$ in the $(n-1)$-th relay-set; the second maximization is over all bit-rates that meet the transmission error probability constraint; and the minimization is between the bit-rate from node (n,i) to $(n-1,j)$ and the bit-rate from node $(n-1,j)$ to the destination.

For the lognormal idealized BSP and urban idealized BSP, the performance of BSP is determined by the value of J at the source. As described above, the value of the selection metric for the implementation of BSP is complicated by the possibility that while node (n,i) may select node $(n-1,j^*)$ as the best next hop, if node $(n-1,j^+)$ is able to decode the packet, it may be better suited to transmit the packet than $(n-1,j^*)$. Specifically, consider $R_{(n,i),(n-1,j*)} > R_{(n,i),(n-1,j^+)}$ and $J_{(n-1,j^*)} < J_{(n-1,j^+)}$, but with

$$\max_{\left\{B:f\left(R_{(n,i),(n-1,j^*)}\geq \texttt{PROB\_THRESH}\right)\right\}} \min\left(B, J_{(n-1,j^*)}\right) > \max_{\left\{B:f\left(R_{(n,i),(n-1,j^+)}\geq \texttt{PROB\_THRESH}\right)\right\}} \min\left(B, J_{(n-1,j^+)}\right).$$

In this case, node (n,i) will select a bit-rate with the intention of transmitting to $(n-1,j^*)$. However, if $(n-1,j^+)$ can decode the packet, then since $J_{(n-1,j^+)} > J_{(n-1,j^*)}$, it is best suited to transmit. Of course, the probability that node $(n-1,j^+)$ will be able to decode the packet will be below `PROB_THRESH`. Thus, for performance comparison, we use the minimum bit-rate that the packet was transmitted at, which, in general is not the same as the value of J at the source. As is the case in Section 4.2, the reason for the complication is that (3) does not account for the probabilistic nature of transmissions.

We assume that the least-hop approach keeps the bit-rate fixed. Thus, the two approaches are compared by comparing the throughput of BSP to one.

Finally, we assumed that $\texttt{PROB\_THRESH} = 10^{-3}$ (note that this is packet error, not bit-error), and assume bit-error, SNR, bit-rate relationship as specified by M-ary QAM scheme is used where M is allowed to vary from 2 to 4096 providing transmission rate multiplier from 1 to 12 times. The relationship between SNR and loss probability used is provided on page 327 in [8] for $M \geq 4$, and on page 298 for $M = 2$.

Figure 4 shows the performance of BSP under this selection metric. As is the case for the max-min SNR, the lognormal idealized BSP does not provide as much of an improvement as the urban idealized BSP. Nonetheless, it shows that in this setting BSP improve the throughput by a factor of 2 to 3. In the idealized and implemented urban case, the throughput is shown to be substantially higher than the lognormal case with factor of 2 to over 10 improvement.

As is the case in Section 4.2, the implemented urban case shows more improvement than the idealized case. As discussed above, the reason for this is that (2) does not account for the probabilistic nature of packet transmission.

4.4 Minimum end-to-end delay

Maximizing the throughput is equivalent to finding the path that has the highest bottleneck bit-rate. However, bit-rate and delay are reciprocals. Hence, maximizing bit-rate is the same as finding the path that has the smallest bottleneck transmission delay. Here we extend the focus on a single link to all links, specifically,

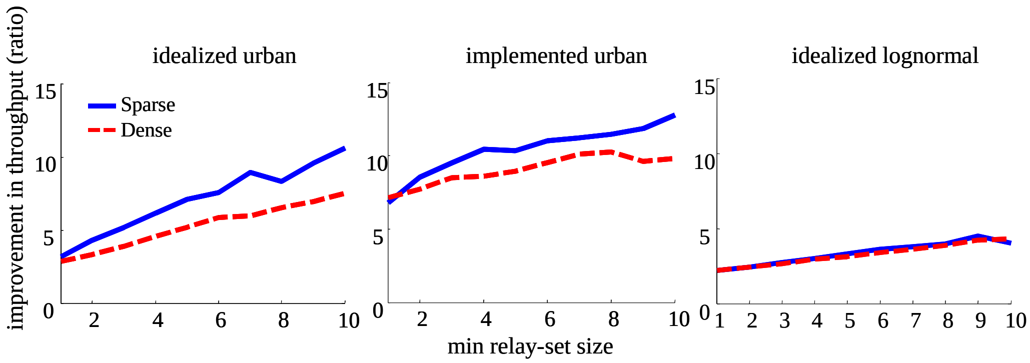

Figure 4. Max throughput. The average ratio of the throughput of BSP to the throughput of least-hop routing.

we examine the total end-to-end delay, i.e., the sum of each transmission delay (we do not consider queuing or processing delay). One motivation for this selection metric is to reduce the interference caused by the packet delivery. Clearly, the longer that a node is transmitting a particular packet, the more network capacity is being used by this node.

While the previous selection metric imposed a transmission error constraint, here the expected delay is considered and it is assumed that if a packet is lost due to transmission error, the total end-to-end delay is T, where T is a large number. The motivation for this is that if a packet is lost, then the transport layer will be forced to retransmit, resulting in a large delay. T is further discussed later.

Here $J_{(n,i)}$ is defined as the expected sum of the transmission delays from node (n,i) to the destination. Furthermore, let $J_{(n,i)}(B)$ be the expected delay from node (n,i) to the destination if node (n,i) transmits at bit-rate B. Thus

$$J_{(n,i)}(B) \tag{4a}$$

$$= \frac{\text{packet size}}{B}\left(f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right) + \left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right)\right)f\left(R_{(n,i),(n-1,\mathcal{I}(2))}X,B\right)\right. \tag{4b}$$

$$\left.+\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right)\right)\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(2))}X,B\right)\right)f\left(R_{(n,i),(n-1,\mathcal{I}(3))}X,B\right)+\cdots\right) \tag{4c}$$

$$+\left(f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right)J_{\mathcal{I}(1)} + \left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right)\right)f\left(R_{(n,i),(n-1,\mathcal{I}(2))}X,B\right)J_{\mathcal{I}(2)}\right. \tag{4d}$$

$$\left.+\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right)\right)\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(2))}X,B\right)\right)f\left(R_{(n,i),(n-1,\mathcal{I}(3))}X,B\right)J_{\mathcal{I}(3)}+\cdots\right) \tag{4e}$$

$$+T\left(\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right)\right)\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(2))}X,B\right)\right)\cdots\right). \tag{4f}$$

To see this, note that if the transmission is successfully, then the delay from node (n,i) to the next relay-set is $\frac{\text{packet size}}{B}$. The probability of experiencing this delay is given in (4b-4c). Furthermore, if transmission is successful, it experiences a further delay of $J_{(n-1,j)}$. However, the node in the next relay-set that transmits depends on which node receives the packet and its relative values of J. Specifically, if node $(n-1, I(1))$ decodes the packet, a delay of $J_{(n-1,I(1))}$ will be experienced. If the packet does not reach node $(n-1, I(1))$, but does reach $(n-1, I(2))$, then a delay of $J_{(n-1,I(2))}$ is expected. The probability of such events is given in *(4d-4e)*. Finally, (4f) accounts for the delay that occurs when the transport layer is forced to retransmit the packet. This event would occur with probability $\left(\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(1))},B\right)\right)\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(2))},B\right)\right)\cdots\right)$.

Given $J_{(n,i)}(B)$ we define $J_{(n,i)} = \min_B J_{(n,i)}(B)$. And, the node with the smallest $J_{(n,i)}$ transmits the packet.

In the simulations shown, $T = 100$. However, different values of T are possible and can result in some difference in performance. Specifically, if T is very large, then, in order to make $J_{(n,i)}$ small, $f\left(R_{(n,i),(n-1,\mathcal{I}(1))},B\right)$ will need to be very close to one. Hence, a conservative bit-rate will be selected. On the other hand, if T is smaller, then the penalty of a transmission error is not so great and the bit-rate can be increased. Thus, T acts much like a constraint on the transmission error probability. However, in some settings, T may be a more intuitive parameter than the transmission error probability.

Figure 5 shows the performance under this selection metric. It is assumed that the least-hop approach used a fixed bit-rate. In the idealized and implemented urban cases, the delay is reduced by a factor of

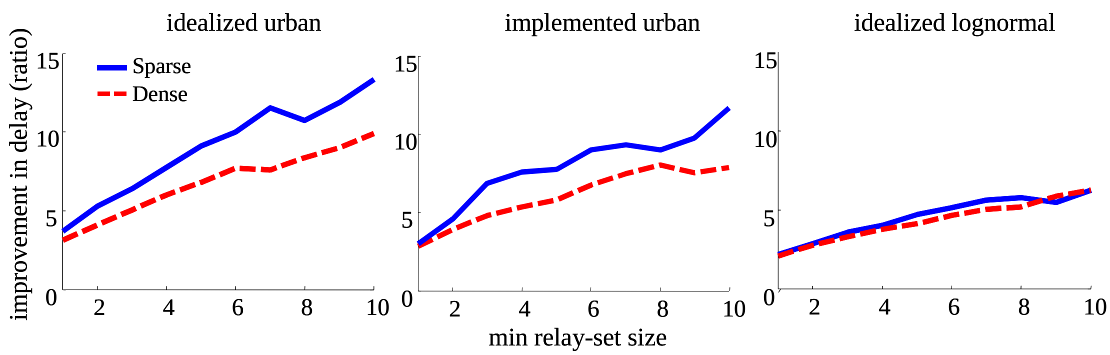

Figure 5. Min delay. The average ratio of the end-to-end delay of least-hop routing to the end-to-end delay with BSP.

between 3 and 14. In the lognormal case, the delay is reduced by a factor of 3 to 6. The reason for the difference is the same as discussed above.

Note that Figure 5 shows a small difference between the idealized urban and implemented urban cases. This contrasts the pervious metrics where the implemented case gave better performance than the idealized case. The reason for this is that the selection metric (4a-4f) does account for the probabilistic nature of transmission.

4.5 Minimizing the total transmission power subject to per link SNR constraint

In many situations it is desirable to reduce the transmission power. For example, if the nodes are battery powered, then reducing the transmission power will lead to a longer lifetime. Similarly, reducing the total transmission power can reduce the interference imposed by the packet delivery. Of course, if the transmission power is reduced by too much, transmission errors will result. Hence, it is necessary to impose a constraint on the transmission error probability. However, since the bit-rate is fixed, it is straight forward to convert a constraint on transmission error to a constraint on SNR.

Thus, we define $J_{(n,i)}$ to be the total power required to deliver a packet from node (n,i) to the destination while meeting per link SNR constraint. Then

$$J_{(n,i)} = \min_{(n-1,j)} \frac{SNR^*}{R_{(n,i),(n-1,j)}} + J_{(n-1,j)}, \tag{5}$$

where SNR^* is the per link SNR constraint. Note that the actual SNR is $R_{(n,i),(n-1,j)} \times X$, where X is the transmission power. Thus, if $X = \frac{SNR^*}{R_{(n,i),(n-1,j)}}$, then the SNR constraint will be met.

The node with the smallest $J_{(n,i)}$ transmits with power $\frac{SNR^*}{R_{(n,i),(n-1,j^*)}}$ where $(n-1, j^*)$ achieves the minimization.

In the idealized cases, the total transmission power is the value of J at the source. However, as is the case in many of the previous metrics, in the implementation, the total power may be less than the value J at the source. Thus, to evaluate the performance of the implementation, each transmission power is summed. In the case of least-hop routing, J can also be computed, however, the minimization is trivial since there is only one possible next hop. That is, in performance of the least-hop case is $\sum_{i=0}^{N-1} \frac{1}{R_{i,i+1}}$ where $R_{i,i+1}$ is the SNR from the i-th hop to the $(i+1)$-th hop and there are N hops.

Figure 6 compares the performance of the BSP to least-hop in the different scenarios. Here we see that BSP yields dramatic performance improves over least-hop routing. Even the lognormal idealized case shows an improvement of a factor 3 to 30.

Note that this selection metric is, in some ways, similar to the max-min SNR metric examined in Section 4.2 which also lead to large performance improvements. However, here the performance gains surpass those found in Section 4.2. One obvious reason is that here we consider all links from end to end, whereas, the max-min SNR focuses on a single, worst, link. However, another, more significant reason is that the least-hop

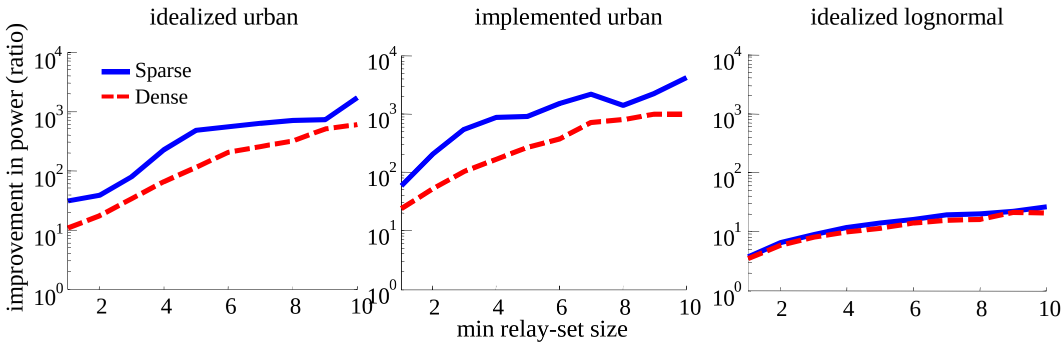

Figure 6. Min power. The average ratio of the total end-to-end transmission power of least-hop routing to the total end-to-end transmission power with BSP.

approach we consider uses a fixed transmission power. A more intelligent least-hop approach would vary the transmission power according to the channel gains. Indeed, such an approach is followed in [15]. If such an MAC was used, then the performance gains found here would be more similar to those found in Section 4.2.

Again, note that (5) does not account for the probabilistic nature of transmissions and so the implementation shows better performance than the idealized case.

4.6 Minimum total energy

The final selection metric considered is a combination of the above metrics. Specifically, we consider the total energy, which is the product of the transmission power and the duration of the transmission. This metric is motivated by the need of battery power nodes to conserve energy as well as a way to reduce interferences.

Let $J_{(n,i)}$ be the expected energy required to delivery the packet to the destination from node (n,i). Furthermore, let $J_{(n,i)}(B,X)$ be the expected total energy required to deliver the packet from node (n,i) to the destination if node (n,i) transmits at bit-rate B and with transmission power X. Then

$$\begin{aligned}J_{(n,i)}(B,X) = X \times \frac{\text{packet size}}{B}&\left(f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right)+\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(1))1}X,B\right)\right)f\left(R_{(n,i),(n-1,\mathcal{I}(2))}X,B\right)+...\right.\\&+\left(f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right)J_{\mathcal{I}(1)}+\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right)\right)f\left(R_{(n,i),(n-1,\mathcal{I}(2))}X,B\right)J_{\mathcal{I}(2)}+...\right.\\&\left.+T\left(\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(1))}X,B\right)\right)\left(1-f\left(R_{(n,i),(n-1,\mathcal{I}(2))}X,B\right)\right)\cdots\right)\right.,\end{aligned}$$

where T is a parameter that represents the energy required to retransmit the packet due to transport layer retransmission. As in the minimum end-to-end delay metric examined in Section 4.4, T is set to a large value and can be used to control the probability of transmission error. The minimum energy selection metric can also be posed as a minimum energy with a constraint on the transmission error probability. The results of such a selection metric are similar to what is shown here.

Once $J_{(n,i)}(B,X)$ is known, then $J_{(n,i)}$ is found via $J_{(n,i)} = \min_{B,X} J_{(n,i)}(B,X)$. And, like always, the node with the best $J_{(n,i)}$ is the one that transmits the data packet. In this case the best node transmits with power X and bit-rate B where X and B result in the maximum value of $J_{(n,i)}(B,X)$.

In the idealized cases, the value of J at the source is the total energy, but for the implementation, the total energy is found by summing the transmission power divided by the bit-rate. For the least-hop case, it is assumed that the bit-rate and transmission power is fixed. The total energy is found by computing $J_{(n,i)}$ but where the relay-sets are collapsed to the least-hop path.

Figure 7 shows the performance under the minimum energy metric. The urban cases are able to achieve dramatic reduction in energy, often well over an order of magnitude. The lognormal case shows an improvement of approximately one order of magnitude.

Note that this metric does account for the probabilistic nature of transmission.

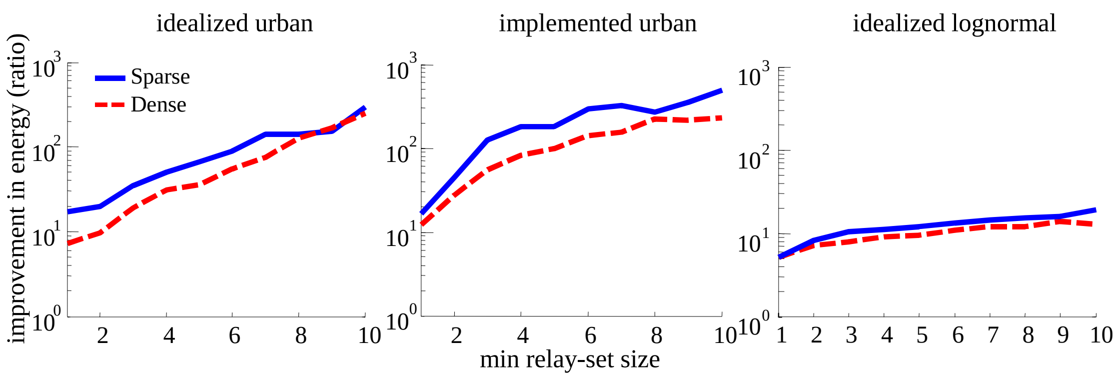

Figure 7. Min energy. The average ratio of the total end-to-end transmission energy of least-hop routing to the total end-to-end transmission energy with BSP.

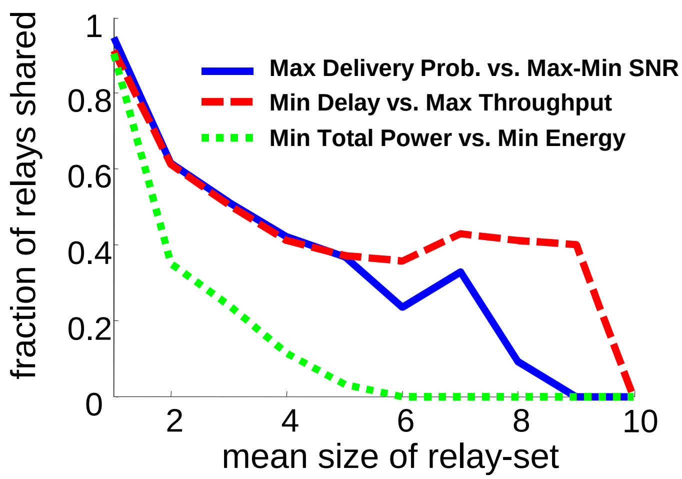

Figure 8. If different selection metrics are used, then, in general the path selected are different. However, some nodes might be selected regardless of the metric. For example, two different metrics might select the same nodes to act as relays. This plot shows the fraction of nodes that are selected by both of the indicated selection metrics.

5 Differences between selection metrics

A final issue to be addressed is how the metrics differ. While the metrics clearly have different objectives, it is possible that they result in packets following the same path. Figure 8 shows the average fraction of the path that two selection metrics share. For example, the minimum total power is compared to the minimum total energy. We see that for scenarios where the mean relay-set size is 2, on average about 40% of the path are shared. Furthermore, for scenarios where the mean relay-sets size is 9, the paths are completely disjoint (except for the source and destination, which are not included in the calculation).

Figure 8 compares the paths for several pairs of similar selection metrics. Specifically, since total power and total energy are similar concepts, the nodes utilized in the transmission might also be similar. Maximizing throughput, which is the max-min link delay, is similar to minimizing the end-to-end delay. And, maximizing the probability of delivering the packet to the destination is similar to maximizing the SNR. However, in all these cases, the paths selected are quite different, especially for large relay-set sizes. We can conclude that while the metrics explored all use the SNR, the way in which the SNR is used can lead to significant difference in the paths selected.

6 Conclusion

This paper examined several node selection metrics for the best-select protocol (BSP). It is found that BSP can be used to increase performance in a number of ways. While the exact improvement depends on the environment, improvements of a factor of 2 to 10 is not uncommon. When considering SNR, transmission power, or energy, improvements of two orders of magnitude are not uncommon.

This investigation considered several scenarios. Specifically, an idealization of BSP was considering in a lognormal fading scenario and in a scenario where the channel gains were from simulations of an urban area. In this first case, the nodes were assumed to be stationary, while in the second case, the nodes followed a urban mobility. A third scenario used a QualNet implementation of BSP. In this case the channel gains and mobility is the same as the urban idealized case. Finally, in each scenario, two node densities were considered. Summarizing the results, it is found that density does not have a strong or systematic impact on the improvements that BSP can achieve. However, in some case, it is found that lower density can result in better performance. On the other hand, the propagation and implementation have an impact on the performance improvement. Specifically, the urban idealized case results in far large performance improvements than the lognormal case. The main reason that the idealized urban case results in larger gains than the lognormal case is that the lognormal case did not include mobility. As nodes move, the links selected by least-hop routing can experience high path loss. Hence, BSP makes a large difference when nodes are mobile.

References

[1] S. Bohacek, J. Hespanha, J. Lee, C. Lim, and K. Obraczka, "Enhancing security via stochastic routing," in *Proc. Of the 11th IEEE Int. Conf. On Comput. Communications and Networks*, 2002.

[2] B. Zhao and M. C. Valenti, "Practical relay networks: A generalization of hybrid-ARQ," *IEEE Journal on Selected Areas in Communications*, vol. 23, pp. 7–18, 2005.

[3] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity - Part I: System description," *IEEE transactions on communication*, vol. 51, pp. 1927–1938, 2003.

[4] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity - Part II: Implemenation asepcts and performance analysis," *IEEE transactions on communication*, vol. 51, pp. 1939–1948, 2003.

[5] J. Luo, R. S. Blum, L. J. Greenstein, L. J. Cimini, and A. M. Haimovich, "New approaches for cooperative use of multple antennas in ad hoc wireless networks," in *Proceedings of IEEE Vehicular Technology Confernece (VTC '04-Fall)*, Sept. 2004.

[6] J. Kim and S. Bohacek, "Multi-hop cooperative relaying for mobile networks," in *Submitted*, 2004.

[7] D. P. Bertsekas, *Dynamic Programming and Optimal Control.* Belmont, MA: Athena Scientific, 2000.

[8] T. Rappaport, *Wireless Communication.* Pearson Education, 2002.

[9] V. Sridhara, J. Kim, and S. Bohacek, "Simulation of mobile ad hoc wireless networks," 2004. Available at :http://www.eecis.udel.edu/ bohacek/UDelModels/pubs/SimOfMANETs.pdf.

[10] D. Helbing, "Sexual differences in human crowd motion," *Nature*, vol. 240, p. 252, 1972.

[11] D. Helbing, "The statistics of crowd fluids," *Nature*, vol. 229, p. 381, 1971.

[12] G. K. Still, *Crowd Dynamics.* PhD thesis, university of warwick, 2000.

[13] J. Kim and S. Bohacek, "Simulation of mobile ad hoc wireless networks," in *Submitted*, 2005.

[14] S. Bohacek, A. Ilic, and V. Sridhara, "On the predictability of link lifetimes in urban MANETs," in *3rd Intl. Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks*, 2005.

[15] G. Holland, N. Vaidya, and P. Bahl, "A rate- adaptive MAC protocol for wireless networks," in *Proceedings of Mobile Computing and Networking*, pp. 236–251, 2001.