The impact of the timeliness of information on the performance of multihop best-select

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***Abstract*— Cooperative relaying enables nodes to actively cooperate to deliver packets to their destination. This cooperation allows nodes to take advantage of the diversity provided by variations in the channel gains between nodes. Best-select, a particular type of cooperation, has been shown to result in significant gains in the performance of source-to-destination communication. However, this increase in performance is achieved by exchanging channel gain measurements, which requires overhead. One way to reduce this overhead is to exchange channel gain measurements less frequently. This paper examines the trade-off between performance and the frequency of exchanging channel gains. This investigation focuses only on the channels that are impaired by multipath fading and shadow fading.**

I. 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 packets are forwarded along each route either probabilistically, or the routes are used as precomputed backups [1], [2]. In any case, in traditional routing, nodes act alone to forward the packet to its 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 [3] 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 [4], [5]. However, if the channels are known, then a simple and good performing approach is to allocate all the power to the node that has the best channel to destination [6]. Such an approach is known as best-select relaying.

Best-select protocol (BSP) is an implementation and a multihop extension of best-select relaying [7]. BSP makes active use of channel measurements to select the best end-to-end path. A distinguishing feature of BSP is that it is highly dynamic; channel measurements are repeatedly made and the path that packets take varies as the channel varies. In this way, BSP is able to take advantage of diversity and achieves dramatic improvement over traditional least-hop routing that finds a single path and utilizes the path until it breaks. In [8], it was found that BSP provides large performance improvements over least-hop routing. For example, it was found that BSP has the potential to find paths that provide 5-10 times higher throughput, impose 5-10 times less delay, utilize 10-1000 times less power, and consume 10-100 times less energy than traditional least-hop routing.

As mentioned, best-select relies on the dissemination of channel measurements. Specifically, the version of best-select considered in [8] exchanges channel information between adjacent relay-sets every time a packet is delivered. On the one hand, this exchange of channel information results in overhead and detracts from the overall performance. While on the other hand, it is the exchange of channel information that allows the best path to be selected and leads to the improvements in performance. This paper investigates the relationship between performance and the rates at which channel information is exchanged. Several schemes to reduce overhead are considered. Specifically, while BSP exchanges channel information with every packet delivery, here the impact of exchanging channel information less regularly is investigated. Also, as explained in the next section, the direction of the exchanges (downstream or upstream) can be changed. The impact of the direction of the information exchange is investigated. Also, the impact of only "good" nodes exchanging channel information and the impact of exchanging channel information only when the current path degrades beyond a threshold is studied. It should be noted that, technically, best-select implies that the best path is selected. However, the schemes investigated here might not exchange information frequently enough to ensure that the paths used are indeed the best. Nonetheless, we still refer to these methods as multihop best-select (MBS) schemes.

The performance of any cooperative relaying scheme is dependent on the availability of diverse paths that provide time-varying performance. Thus, the propagation environment and node mobility play an important role in the behavior of any cooperative diversity scheme. Here, the focus is restricted to the diversity provided by multipath fading and shadow fading. Furthermore, we examine regular networks where there are M nodes in each relay-set and N hops between the source and the destination, and where the channels between nodes in adjacent relay-sets are i.i.d.

The paper proceeds as follows. In the next section a brief overview of how channel gain information is exchanged is provided. In Section III, the channel models are discussed. In Section IV, the ideal performance of MBS is examined while in Section V the performance with outdated channel information is presented. Section VI investigates the relationship between performance and the rate of overhead packets required to achieve that performance. Finally, Section VII provides some concluding remarks.

II. Channel gain exchange schemes for multihop best-select

As mentioned above, the MBS schemes studied here group 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. The decision as to which node is best suited to transmit depends not only on the channel gains between nodes within the n-th relay-set and the $(n-1)$-th relay-set (which we denote as $R_{(n,i),(n-1,j)}$), 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 exchanged between nodes. Instead, the downstream channel information is encapsulated into a scalar, denoted J. The downstream channel information from node (n, i) is denoted $J_{(n,i)}$ and depends on the metric used to select paths. While many selection metrics are possible, in this paper, only the max-min channel gain selection metric is considered. In this case, $J_{(n,i)}$ is the worst channel gain along the best path from node (n, i) to the destination. That is, for each path from (n, i) to the destination, there is a worst link, the link with the lowest channel gain. With this metric, the objective is to select the path whose worst link is better than all other paths' worst links. Thus, $J_{(n,i)}$ satisfies

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

To determine which node within the relay-set should transmit, the nodes within adjacent relay-sets must exchange channel information. BSP accomplishes this by including channel gain information within the RTS-CTS packets. Specifically, when the n-th relay-set desires to send a packet, all nodes within the relay-set transmit a RTS to all nodes within the $(n-1)$-th relay-set. These transmissions occur simultaneously using with each node using an orthogonal channel (e.g., using CDMA). Each node in the $(n-1)$-th relay-set receives all the RTSs and records the channel gains over each channel. 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 the J of the sender. Each node in the n-th relay-set receives these CTSs. 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.

Note that for each exchange of RTSs and CTSs, the channel information propagates one hop upstream. To put it another way, let $J_{(n,i)}(k)$ be the value of $J_{(n,i)}$ after the k-th packet is delivered. Then, $J_{(n+1,j)}(k+1)$ is a function of $J_{(n,i)}(k)$. Similarly, $J_{(n+2,j)}(k+2)$ is a function of $J_{(n,i)}(k)$. Thus, if the channels are static, $J_{(n,i)}(k)$ will correctly reflect the downstream channels after n data packet deliveries (i.e., when $k = n$). In the dynamic case, if data is sent at a high rate, then J will be rapidly updated and accurately reflect downstream channel gains. However, if data is sent quickly, then there may be little benefit to exchanging channel gain information with every packet delivery. Instead, channel gain information can be exchanged after the nodes move X meters. We call this approach *downstream exchanges with period X*.

An alternative approach is to perform similar channel exchanges, but instead the exchange starts at the destination and proceeds to the source. Specifically, each node in the $(n-1)$-th relay-set broadcasts a packet that includes its J. The nodes within the n-th relay-set receive these packets, measure the channel during the reception, and determine their J via (1). These nodes then transmit the channel gain information to the $(n+1)$-th relay-set. Furthermore, each node records its best next hop, i.e., the $(n-1, j)$ that acheives the maximum in (1). When a data packet is received by a node, it transmits the data packet directly to this it to its best next hop. Note that while n *downstream exchanges* are required for the n-th relay-set to have the correct value of J, in this scheme, all nodes learn the correct value of J after one exchange. When the exchanges are performed when the nodes move X meters, this scheme is called *upstream exchanges with period* X.

Instead of initiating channel exchange information periodically, the destination could initiate an exchange when the worst channel gain experienced by a data packet is found to degrade. Specifically, within the packet header is included $J_{(N,1)}$, the expected worst channel gain to be experienced by the packet (recall that there are N hops from the source to the destination). Furthermore, as the packet traverses the network, the worst channel gain actually experienced by the packet is determined and placed in the header. The destination initiates a channel gain exchange if $Q \times MBSG\left(M,N\right) > J_{(N,1)} -$ *actual channel gain*, where Q is a parameter and $MBSG\left(M,N\right)$ is the mean improvement, in dB, of the worst channel gain along the best path as compared to the worst channel gain along an arbitrary path when there are N hops from source to destination and M nodes within each relay-set (the value of $MBSG$ is determined in Section IV). This scheme is called *upstream exchange on event of size* Q.

During an upstream exchange of information, if a node determines its J and finds that it is below a threshold, then it is unlikely that this node will be selected as the best node within the relay-set. In this case, there is no need for this node to take part in the exchange of channel gain information, thereby reducing overhead. One drawback of such an approach is that there is a possibility that no nodes within the relay-set will have a J that is larger than the threshold, and hence none of the nodes in the relay-set will exchange channel gain information, breaking the chain of exchanges. To remedy this, when a node within the n-th relay-set hears a broadcast of Js from the $(n-1)$-th relay-set, but does not hear any nodes within the n-th relay-set broadcast their J, the node broadcasts it J regardless of its value. This scheme is called *upstream exchanges between good nodes with period* X, and is further examined in Section VI.

III. Channel models

This paper investigates the relationship between the performance of multihop best-select and the frequency of channel gain information exchanges. This relationship is dependent on how much the channels change between exchanges of channel gain information. Since channel gain varies as a function of position, the variation of the channel gains depends on how far nodes move between the exchanges. The movement of nodes impacts the channel gain in two ways. First, as nodes move, the distances between nodes changes, and hence, the path loss between nodes changes. Second, when nodes move, the multipath and shadow fading changes. The first effect is dependent on the details of the node mobility . For example, the variation of the distances between vehicles within a platoon that are driving down a highway will be quite different from the variation of the distances between pedestrians on their lunch break. This paper only examines the impact of the variation of channel gains due to shadow fading and multipath fading. The impact of the variation of the internode distances is left as future work.

Thus, the channel gain is $\frac{1}{d^{\alpha}}\left(S \times 10^{L/10}\right)$, where S accounts for the multipath fading, L accounts for the shadow fading, α is the path loss exponent, and d is the distance between nodes, which is assumed to be fixed. Since only ratios of channel gains are examined, the exact value of d and α will not be relevant. Furthermore, in order to distinguish the impact of the multipath fading and the shadow fading, we consider two different models, one where the channel gain is $\frac{1}{d^{\alpha}}S$ and one where the channel gain is $\frac{1}{d^{\alpha}}10^{L/10}$.

Multipath fading is modeled as a sum of complex exponentials. More specifically, the gain due to multipath fading at location x is $S\left(x\right) = C \times \left|\sum_{n=1}^{K} \exp\left(-2\pi \frac{c}{\lambda} i x \sin\left(\theta_n\right) + i\phi_n\right)\right|^2$, where λ is the RF wavelength, c is the speed of light, and K is the number of echoes. We assume $K=20$, which results in the stationary distribution of S being approximately exponential. As is often assumed [9], the values of θ_i and ϕ_i are uniformly distributed between 0 and 2π. Finally, C is selected so the mean of S is 1.

As compared to multipath fading, there has been little work on modeling the variation of shadow fading. In [10], the log of the shadow fading is modeled as an Ornstein-Uhlenbeck process. Similarly, in [11], L is modeled as a first order autoregressive model. Following this work, we model

$$dL\left(x\right) = -\alpha L\left(x\right)dx + 2\alpha\sigma dB\left(x\right),$$

where B is Brownian motion and $\frac{d}{dx}$ is the derivative with respect to distance. Given this model, L is Gaussian with autocovariance

$$\begin{aligned}&E\left(\left(L\left(x\right)-E\left(L\left(x\right)\right)\right)\left(L\left(0\right)-E\left(L\left(0\right)\right)\right)\right)\\&=\sigma^2\exp\left(-\alpha\left|x\right|\right).\end{aligned}$$

and mean given by $E\left(L\left(x\right)\right) = 0$. Furthermore, if at position 0 it is known that L is Gaussian with mean

$E\left(L\left(0\right)\right)$ and variance $var\left(L\left(0\right)\right)$, then [12]

$$\begin{aligned} &var\left(L\left(x\right)\right) = \exp\left(-2\alpha\left|x\right|\right) var\left(L\left(0\right)\right) \\ &+ \sigma^2\left(1 - \exp\left(-2\alpha\left|x\right|\right)\right) \\ &E\left(L\left(x\right)\right) = \exp\left(-\alpha\left|x\right|\right) E\left(L\left(0\right)\right). \end{aligned} \tag{2}$$

This expression also holds if the exact value of the channel is known at position 0, i.e., $var\left(L\left(0\right)\right) = 0$. In [13], it was found that $\alpha = 1/10\ \mathrm{m}^{-1}$. Furthermore, σ has been found to range from 4 dB to 12 dB. In this investigation, $\sigma = 8$ dB.

IV. Ideal Performance

As shown in [7], the ideal performance of multihop best-select can be computed as follows. Let $\Gamma\left(u\right)$ be the survival function of the channel gain (i.e., $\Gamma\left(u\right)$ is the probability that the channel gain is above u). If there are N hops between the source and destination and each relay-set has M nodes, then the survival function of the max-min channel gain is $T_{M,N}\left(\Gamma\left(u\right)\right)$,where $T_{M,N}$ is determined as follows. Define the $(M+1) \times (M+1)$ matrix $\Phi_{q,M}\left(i,j\right) := \binom{M}{j}\left(1-q^i\right)^j q^{i(M-j)}$, where the indexes i and j run from 0 to M and $q = 1 - \Gamma\left(u\right)$. Similarly, define $\Phi_{q,M}\left(1,:\right)$ to be the second row of $\Phi_{q,M}$, i.e, $\Phi_{q,M}\left(1,:\right) := \left[\begin{array}{ccc} \Phi_{q,M}\left(1,0\right) & \cdots & \Phi_{q,M}\left(1,M\right) \end{array}\right]$, and define the $(M+1) \times 1$ vector $\phi_{q,M}\left(i\right) := 1 - q^i$. Then, as shown in [7], $T_{M,N}\left(r\right)$ is the product[1] $T_{M,N}\left(r\right) = \Phi_{1-r,M}\left(1,:\right)\left(\Phi_{1-r,M}\right)^{N-2}\phi_{1-r,M}$.

We define the multihop best-select channel gain (*MBSCG*) (in dB) over a network with N hops and M nodes in each relay-set to be the average of the minimum channel gain along the best path. Thus, since $T_{M,N}\left(\Gamma\left(u\right)\right)$ is the survival function of the max-min channel gain, $-dT_{M,N}\left(\Gamma\left(u\right)\right)$ is the pdf of the max-min channel gain, hence

$$MBSCG_{\Gamma}\left(M,N\right) = -\int_{-\infty}^{\infty} u\ dT_{M,N}\left(\Gamma\left(u\right)\right),$$

where u is the channel gain in dB. It is of interest to compare *MBSCG* to the minimum channel gain that would result if a single arbitrary path was selected. To this end, define the multihop best-select gain ($MBSG$) as

$$\begin{aligned} &MBSG_{\Gamma}\left(M,N\right) \\ &= MBSCG_{\Gamma}\left(M,N\right) - MBSCG_{\Gamma}\left(1,N\right), \end{aligned}$$

[1]While this is explained in more detail in [7], one way to understand this is to recognize that the number of nodes in the n-th relay-set that have a path to the source such that every channel along the path has channel gain greater than u is a Markov chain. Φ is the state transition matrix for this Markov chain. The initial state of this Markov chain is 1 (i.e., the source has exactly 1 such path). $\phi_{q,M}\left(i\right)$ is the probability of the destination having a path to the source with channel gains above u conditioned on there being i nodes in the first relay-set that also have such paths.

where $MBSCG\left(1,N\right)$ is the expected minimum channel gain, in dB, along a path with only one node per relay-set, i.e., without best-select.

If the channel is impaired only by shadow fading, then Γ is the survival function of a Gaussian random variable with mean 0 and standard deviation 8. Similarly, if the channel is only impaired by multipath fading, then $\Gamma\left(u\right) = \exp\left(-10^{u/10}\right)$.

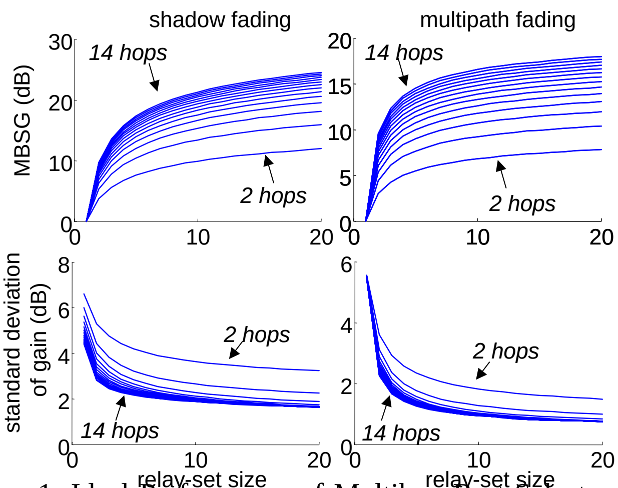
The upper plots in Figure 1 show the *MBSG* for several sizes of relay-sets and lengths of connections. As expected, best-select is able to provide considerably better channel gain than an arbitrary path. Furthermore, as the length of the connection increases, the improvement over an arbitrary path increases. There are two reasons that longer paths provide more improvement. First, the performance of a single path decreases with path length. Second, for moderately long paths, the performance of best-select increases with the length of the path. Note that the first cause is intuitive; when using a single path, the longer the path, the more the chance of finding a bad link. However, the second cause is counter-intuitive. While this is further explored in [7], the idea is that the first and last hops are the most fragile; there are only M links across these hops, whereas there are M^2 links crossing other hops. As the paths grow longer, the impact of the fragility imposed by the ends is reduced since it is possible to find good paths between the best two end links, that is, longer paths allow more flexibility in crossing the first and last hops.

In a similar way as *MBSG* can be determined, the variance of the best-select gain can be computed (i.e., the variance of the difference between the best-select channel gain and the average channel gain over an arbitrary path). Figure 1 also shows the standard deviation of the best-select gain. It can be seen that as the size of the relay-sets increases, the mean increases while the standard deviation decreases. The fact that the variance is small for large relay-sets means that it is possible to accurately predict the performance and it is possible to determine how far a suboptimal path is from optimality.

V. The Impact of Outdated Channel Gain Measurements

When the nodes move, the path that once was optimal will become suboptimal and its performance will tend toward that of an arbitrary selected path. On the other hand, if channel gain information is frequently exchanged, then the performance of the selected path will be improved. Here we explore the relationship between the frequency of channel gain exchanges and performance.

First, upstream exchanges with period X are considered. In this case, the optimal path is found with a single upstream



1: Ideal Performance of Multihop Best-Select

channel gain exchange. This same path is used until the nodes move x meters. After which, channel gains are again exchanged and a new optimal path is found.

In the case of shadow fading, the degradation due to infrequent channel gain exchanges can be approximately computed. Specifically, we assume that the worst link along the best path has a channel gain that is *exactly* $MBSCG$ (in actuality, the worst link's channel gain would be random with mean $MBSCG$). From (2), after the node move x meters, the channel gain (in dB) is Gaussian with mean $\exp(-\alpha|x|)\,MBSCG(M,N)$ and standard deviation $\sigma\sqrt{(1-\exp(-2\alpha|x|))}$.

Besides the worst link, when the channel measurements are exchanged all the other links along the optimal path have a channel gain that is at least as good as the worst link. Hence, the log of the channel gain for these links is Gaussian, conditioned on being larger than $MBSCG$. Then, from (2), the pdf of the channel gain of one of these links after the nodes have moved x meters is

$$\int_{MBSCG(M,N)}^{\infty} g\left(v\,|MBSCG(M,N),0,8\right) \times g\left(u|\exp(-\alpha|x|)\,v,\sigma\sqrt{(1-\exp(-2\alpha|x|))}\right)dv.$$

where $g(w|\mu,\sigma)$ is the pdf of a normally distributed random variable with mean μ and standard deviation σ and $g(w|y,\mu,\sigma)$ is the same pdf but conditioned on being larger than y. The CDF can be found in a similar way.

Thus, the distribution of the channel gain over the worst link and the distribution of the channel gain over the other links can be computed. The distribution of the worst channel gain over the path can be computed using standard order statistics computation.

This approximation and the channel gain found through simulation are compared in Figure 2. This plot is explained as follows. Let $U_{M,N}(x)$ be the average worst channel gain along that path that was optimal before the nodes moved x meters. Then, $U_{M,N}(0) = MBSCG(M,N)$, where $MBSCG$ is given above. The fraction of the $MBSG$ achieved by the suboptimal path when the nodes have moved x meters is

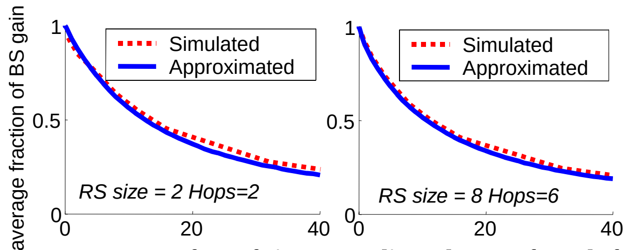
$$\mathcal{F}(x) = \frac{U_{M,N}(x) - MBSCG(1,N)}{MBSCG(M,N) - MBSCG(1,N)}.$$

Thus, $\mathcal{F}(0) = 1$, indicating that all of the multihop best-select gain is achieved. For very large x, we have $U_{M,N}(x) \approx MBSCG(1,N)$, hence $\lim_{x\to\infty}\mathcal{F}(x) = 0$. Finally, Figure 2 shows the average value of $\mathcal{F}$, where $\mathcal{F}$ is averaged over range of positions between channel gain exchanges, i.e., $\frac{1}{X}\int_0^X \mathcal{F}(x)\,dx$, where the channel gains are exchanged every X meters. Figure 2 shows that the approximation closely agrees with values found from simulation. Hence, in the sequel, only this approximation is used.

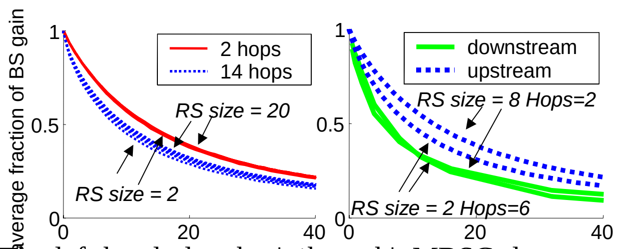
The left-hand plot in Figure 3 shows the degradation of the performance for different networks. As can be seen, the degradation does not vary greatly for different networks. Nonetheless, there is a slight variation. As illustrated in Figure 3, as the length of the path increases, the degradation is slightly more rapid (i.e., the 14-hop case decays faster than the 2-hop case). Furthermore, the larger the relay-set, the slower the degradation. Moreover, this dependence on the size of the relay-set is larger for longer paths (it is hardly noticeable for the 2-hop paths).

While an analytic expression for the degradation of the performance of the downstream update is not available, it can be determined through simulation. Figure 3 compares the performance using downstream and upstream exchanges. As expected, the upstream exchanges perform better than the downstream. If updates occur every meter, then downstream exchanging leads to 5-10% worst performance whereas if updates occur every 4 meters, downstream exchanges yield around 20% worst performance.

Figure 4 shows examples of the degradation of the performance that are similar to those in Figure 3, but for the case where the channels are subject to multipath fading only. The behavior is qualitatively similar to the behavior of the shadow fading case. The only difference is that in the shadow fading case, downstream exchanges displayed less variability for different networks than upstream exchanges do. Whereas in the multipath fading case, the variability of the upstream and downstream exchanges are about the same. Another difference, of course, is that the performance under multipath fading channel decays much faster than the shadow fading case. Specifically, in the case of multipath fading channels, about 40% of *MBSG* is still achieved after the nodes move 0.4λ, or, in this case, 5 cm, whereas in the



2: Comparison of performance degradation found from simulation and computed as described in Section V.

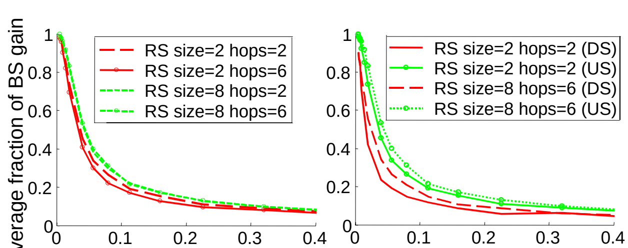


3: The left-hand plot shows how the MBSG decreases for different sized networks. The right-hand plot compares the performance of using downstream channel gain exchanges and using upstream exchanges.

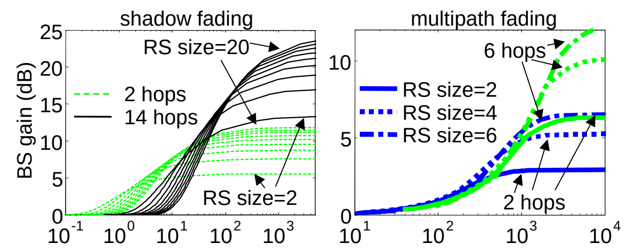
shadow fading case 50% of the *MBSG* is maintained after the nodes move about 10 m. These values are reasonable since in the multipath fading case, the channel gain is uncorrelated after moving 0.4λ, and in the shadow fading case, the autocovariance is 0.3 when nodes are more than 10 meters apart.

VI. Overhead Rate

An alternative way to examine the relationship between performance of multihop best-select and the timeliness of the channel measurements is to compare the performance as a function of the rate at which channel gain exchange packets are transmitted. Here, only upstream exchanges are considered. In the case of periodic and on-event upstream exchanges, one complete exchange requires every node to transmit one packet. Thus, if X is the distance that nodes move between exchange events, then the rate that packets are broadcast to support the exchange of channel gains is $M \times N/X$. Since these channel gain exchanges do not



4: The degradation of the performance as a function of the frequency that channel exchanges are performed. In this case, the channels are subject to multipath fading.



5: The performance of MBS as a function of overhead rate. In the right-hand plot, the solid lines refer to networks with 2 nodes per relay-set, the dashed lines are for relay-sets with 4 nodes, and the dash-dot lines are for relay-sets with 6 nodes.

contain data, $M \times N/X$ is the overhead rate and has units of packets per meter of movement.

The left-hand plot of Figure 5 compares the performance gain of MBS over an arbitrary single path as a function of the overhead rate for networks of length 2 hops and 14 hops when the channel is impaired by shadow fading and periodic upstream exchanges are used. As expected, for low rates of information, MBS provides little improvement over an arbitrary single path, and as the rate of overhead increases, the performance increases, but then levels off. It is interesting to note that for a fixed length path and a fixed overhead rate, there is an optimal relay-set size. For example, for paths with 14 hops, if the overhead rate is fixed at 10 packets per meter of movement, then a network with 20 nodes per relay-set only provides about 1 dB of improvement over an arbitrary single path, whereas at this same overhead rate, if the relay-sets have 2 nodes each, MBS achieves around 6 dB of improvement.

The right-hand plot of Figure 5 is similar to the left-hand plot, but for channels impaired by multipath fading. Also, the right-hand plot is from simulations, while the left-hand plot is calculated as described in the previous section. Note that in the multipath fading case, the performance curves are similar to one another. Thus, in the shadow fading case, if the overhead rate is low, then the performance could be significantly improved by reducing the number of nodes within relay-sets. However, when the channels are impaired by multipath fading, regardless of the overhead rate, there is little improvement in performance if the size of the relay-set is decreased. Similarly, in the shadow fading case, when the performance of long connections is compared to shorter connections, we see that for low overhead rates, shorter connections provide more MBSG than longer connections. However, in the case of channels impaired by multipath fading, long and short channels achieve similar MBSG at low overhead rate.

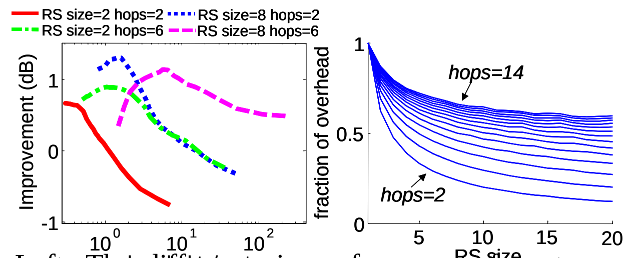
The *upstream exchange on event of size* Q scheme discussed in Section II performs channel gains exchanges only when the minimum channel gain experienced along the connection is significantly worse than the minimum channel gain that was obtained after the channel information was exchanged. The parameter Q affects the frequency of channel gain exchanges. The left-hand plot in Figure 6 shows that when compared to periodic exchanges, this method provides little or no improvement. Figure 6 is for shadow fading; multipath fading is similar. While this scheme does not provide significantly better performance than periodic exchanges, if the speed of the nodes is not known, it is difficult to implement *upstream exchanges with period* X. Figure 6 shows that there is little performance degradation when exchanges are initiated by variations in observed channel gains.

In Section II, the *upstream exchanges between good nodes with period* X method was discussed. For this scheme, the relationship between the *MBSG* and the frequency of exchanges is nearly the same as when simple periodic exchanges are used. However, this scheme potentially requires fewer packets to be transmitted for each exchange. One complication with this scheme is that a threshold must be selected. Recall that nodes that have J above this threshold will broadcast their J during a channel gain exchange, and if no nodes within the relay-set have a J above this threshold, then all nodes within the relay-set will broadcast their J. Clearly, if the threshold is too large, then many relay-sets will have no nodes with J above the threshold, and hence all nodes within the relay-set will broadcast their J. On the other hand, if the threshold is too low, then all nodes will have J above the threshold and, again, all nodes will broadcasts their J. The expected number of nodes that will broadcast their J can be found as follows.

Define the $(M+1)$ dimensional row vector $F_{M,n}(r) := \Phi_{1-r,M}(1,:)\left(\Phi_{1-r,M}\right)^{n-1}$, where Φ is defined in Section IV. Letting Γ be the survival function of the channel gain, then the i-th element of $F_{M,n}(\Gamma(u))$ is the probability that i nodes within the n-th relay-set will have a path to the destination where each link has a channel gain above u (see [7] for details). Thus, the expected number of intermediate nodes that have a $J > u$ is $\sum_{n=1}^{N-1} F_{M,n}(\Gamma(u))\, I$, where I is the $(M+1) \times 1$ vector with $I(i) = i$. Similarly, the probability that none of the nodes within a relay-set will have $J > u$ is $F_{M,n}(\Gamma(u))(0)$, the zeroth element of $F_{M,n}(\Gamma(u))$. Thus, if the threshold is u, then the total number of nodes that will broadcast their J is

$$1 + \sum_{n=1}^{N-1} F_{M,n}(\Gamma(u))\, I + m \sum_{n=1}^{N-1} F_{M,n}(\Gamma(u))(0),$$

where the 1 accounts for the destination which initiates the channel gain exchange. This expression can be computed



6: Left: The difference in performance of *upstream exchange on event of size* Q as compared to *upstream exchange with period* X. Right: The amount that overhead is decreased when *upstream exchanges between good nodes with period* X is used as opposed to *upstream exchange with period* X.

and the value of u that minimizes it can be found. However, in both the shadow fading and multipath fading case, the value of u that achieves the minimum is close to $MBSCG$, hence this value is used. Note that $MBSCG$ can be estimated online by observing channel gains.

The left-hand plot in Figure 6 shows the ratio of the overhead that this scheme requires to the overhead that simple periodic exchanges requires. Hence, for connections that are 2 hops long and have 20 nodes in the relay-set, this scheme will only require 20% of the overhead that periodic exchanges require.

VII. Conclusion

While multihop best-select has the potential to provide substantial improvements in performance, this improvement comes with the price of more overhead. This paper examined the relationship between performance, overhead, and the timeliness of the channel gain measurements. It was found that for small networks, a moderate amount of overhead can provide substantial improvement in performance. However, for larger networks, large amounts of overhead are required to achieve a significant fraction of the potential improvement. On the other hand, a scheme that limits which nodes take part in the relaying can greatly reduce the amount of overhead required.

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