Routing Strategies in Multihop Cooperative Networks

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***Abstract*—The fading characteristics and broadcast nature of wireless channels are usually not fully considered in the design of routing protocols for wireless networks. In this paper, we address the routing issue from a link layer point of view. We focus on a multihop network with multiple relays at each hop and three routing strategies are designed to achieve the full diversity gain provided by the cooperation among relays. In particular, an optimal routing strategy is proposed to minimize the end-to-end outage, which requires the channel information of all the links and serves as a performance bound. An ad-hoc routing strategy is then proposed based on a hop-by-hop relay selection, which can be easily implemented in a distributed way. The outage analysis shows that the performance gap between these two routing strategies increases with the number of hops. To achieve a good complexity-performance tradeoff, an *N*-hop routing strategy is further proposed, where a joint optimization is performed every *N* hops. Simulation results are presented which verify the analysis.**

Keywords- *Routing, Diversity gain, Cooperative networks.*

I. INTRODUCTION

In the last several years, there has been growing interest in multihop wireless networks, either infrastructure-based or ad hoc (for example, see [1-2] and references therein). In previous work on routing in wireless networks, however, the fading characteristics of wireless channels are not taken into full consideration. The channel is usually simplified as "ON" or "OFF" according to some specific SNR threshold and the whole network is modeled as a graph. Most routing protocols were developed based on error-free links aiming at the shortest path or the minimum number of hops (see [3-5]). As pointed out in [6] and demonstrated experimentally in [7-8], however, the wireless channel changes rapidly with time, that is, the 'on-off model' is not accurate for a wireless network. Also, several researchers have confirmed that minimum-hop routing might lead to a path that uses longer range links of marginal quality [9-10]. The broadcast property of wireless transmission is also often ignored.

In the wireless link layer, transmit/receive diversity is an excellent means for overcoming fading. However, in some scenarios the use of multiple antennas might be impractical because of the limited size and power of the individual nodes. Cooperative transmission has been proposed to address this issue; in this case, diversity gain can be achieved through the cooperation among nodes by exploiting the broadcast nature of the wireless medium [11-13].

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In this paper, we investigate the routing issue from the link layer point of view. We focus on a multihop network with multiple relays at each hop, and aim at minimizing the end-to-end (or source-to-destination) outage. Routing strategies are designed to fully exploit the diversity gain provided by the cooperation among relays. In particular, an *optimal routing* strategy is proposed which chooses the path with the minimum end-to-end outage among all possible paths. To achieve this superior performance, the channel state information of all the links is required and a joint optimization needs to be performed. To reduce the amount of required information, an *ad-hoc routing* strategy is proposed where the relay selection is performed in a per-hop manner so that only L-link information is needed at each hop. Not surprisingly, there will be a performance gap between these two routing strategies. To achieve a good complexity-performance tradeoff, an *N-hop routing* strategy is finally proposed, where a joint optimization is performed every N hops.

In a decode-and-forward multihop network with L relays cooperating with each other per hop, the maximum diversity gain is L-fold regardless of the number of hops. The outage analysis of the proposed three routing strategies will show that all of them can achieve full diversity gain. However, the performance gap between optimal routing and ad-hoc routing (or N-hop routing) increases with the number of hops, M. In particular, the outage performance of optimal routing remains constant with an increase in M. In contrast, both ad-hoc and N-hop routing suffer a linear increase in outage. Nevertheless, only a slight performance loss is incurred by ad-hoc routing compared to the optimal one when the number of hops is small; this makes it highly attractive in infrastructure-based multihop networks.

The paper is organized as follows. The system model is described in Section II. In Section III, we propose three routing strategies and analyze the end-to-end outage performance of each. Simulation results are given in Section IV. We also address some implementation issues such as complexity. Finally, Section V summarizes and concludes the paper.

II. SYSTEM MODEL

We consider an idealized M-hop linear network model as shown in Fig. 1. M-1 relay clusters are equally spaced from the source node and the destination node. Each relay cluster includes L relay nodes. We assume that the nodes in a certain relay cluster are close together and the distance between clusters is much larger than the distance between the nodes in any one cluster. Therefore, the effect of large-scale fading can be neglected and only the small-scale fading is considered. Also, each node is equipped with only one antenna.

TDMA is adopted so that only one source/destination pair is active during each particular period. A selective decode-and-forward relaying strategy is assumed; in particular, at each hop, only one relay node is selected to forward the packet according to some SNR thresholds. We also assume that the signal transmitted by a certain node can only be heard by the nodes in its neighboring relay cluster.

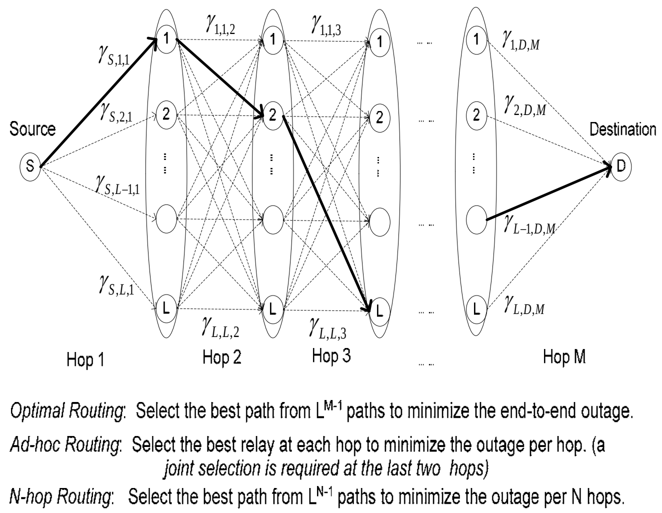

Fig. 1: Linear network model with *M* hops and *L* relays at each hop.

The channel gain of each link is modeled as a complex Gaussian random variable with zero mean and unit variance. The average receive SNR at each relay is then given by $\gamma_0 = 1/\sigma_n^2$, where σ_n^2 is the variance of the additive white Gaussian noise. Let $\gamma_{i,j,k}$ represent the SNR of the signal from relay *i* to relay *j* at hop *k*, *i*, *j*=1,…, *L* and *k*=2,…, *M*-1. $\gamma_{S,j,1}$ and $\gamma_{j,D,M}$, *j*=1,…, *L*, are the SNRs at hop 1 and *M*, respectively; thus, we have $(M\text{-}2)L^2+2L$ i.i.d. links in the network.

In an *M*-hop network with *L* relays at each hop, there are $W=L^{M-1}$ possible paths from the source to the destination. Let $r_k^{(i)}$ represent the relay at hop *k* in path *i*, *i* =1,…,*W* and *k*=1,…,*M*-1. Also assume $r_0^{(i)}=S$, the source, and $r_M^{(i)}=D$, the destination. Obviously each path has a different relay set $\left\{r_k^{(i)}\right\}$ and the corresponding SNR set is given by $\left\{\gamma_{r_{k-1}^{(i)},r_k^{(i)},k}\right\}$. For example, the path marked with the solid line in Fig. 1 chooses relays 1, 2 and *L* at hops 1, 2 and 3, and relay *L*-1 at hop *M*-1. Its relay set is then given by {1, 2, *L*, …, *L*-1}.

In this paper, we focus on the end-to-end outage performance. In particular, the outage probability of path *i*, *i*=1,…, *W*, is given by

$$P_{out}^{(i)} = 1-\prod_{k=1}^{M}\left(1-P_{out,k}^{(i)}\right) = 1-\prod_{k=1}^{M}\left(1-P\left(\gamma_{r_{k-1}^{(i)},r_k^{(i)},k}<\gamma_{th}\right)\right) = P\left(\min_{k=1,\dots,M}\left\{\gamma_{r_{k-1}^{(i)},r_k^{(i)},k}\right\}<\gamma_{th}\right) \quad (1)$$

where $P_{out,k}^{(i)}$ is the outage probability at hop *k* of path *i* and γ_{th} represents the required SNR threshold. The final equation is getting from the fact that $\gamma_{r_{k-1}^{(i)},r_k^{(i)},k}$, *k=1,…, M* are independent random variables. Obviously, the end-to-end outage of an *M*-hop path is limited by the worst hop.

III. ROUTING STRATEGIES AND OUTAGE ANALYSIS

In this section, we provide the details of the three routing strategies and the corresponding outage analysis.

A. Optimal Routing

It has been shown in (1) that the end-to-end outage of path *i* is limited by the minimum SNR of the *M* hops, $\gamma_{\min}^{(i)} = \min_{k=1,\dots,M}\left\{\gamma_{r_{k-1}^{(i)},r_k^{(i)},k}\right\}$. Therefore, to minimize the end-to-end outage of the whole network, the path with the maximum $\gamma_{\min}^{(i)}$ should be chosen. The details are provided below.

Optimal Routing:

> Given *L* and *M*, let $W=L^{M-1}$.
>
> *Initialization:*
>
> Generate all possible paths $\left\{r_k^{(i)}\right\}$, $r_0^{(i)}=S$, $r_M^{(i)}=D$, *i*=1,…,*W*. $\gamma_{\min}^{\max}=0$, $ind^*=0$.
>
> *Recursion:*
>
> For *i*=1:*W*
>
> Calculate $\gamma_{\min}^{(i)} = \min_{k=1,\dots,M}\left\{\gamma_{r_{k-1}^{(i)},r_k^{(i)},k}\right\}$ for path *i*;
>
> If $\gamma_{\min}^{(i)} > \gamma_{\min}^{\max}$
>
> $\gamma_{\min}^{\max} = \gamma_{\min}^{(i)}$; $ind^*=i$;
>
> End if
>
> End loop
>
> Output the optimal path $\left\{r_k^{(ind^*)}\right\}$.

The end-to-end outage of optimal routing is then given by

$$P_{out}^{opt} = P\left(\max_{i=1,\dots,W}\min_{k=1,\dots,M}\left\{\gamma_{r_{k-1}^{(i)},r_k^{(i)},k}\right\}<\gamma_{th}\right) \quad (2)$$

It is not trivial to solve (2) because the *W* paths are usually dependent. For example, in a 4-hop network with *L*=3, paths {1, 2, 2} and {1, 3, 2} share the same links at hop 1 and hop 4 so that their SNR sets both include $\gamma_{S,1,1}$ and $\gamma_{2,D,4}$. Actually, the *W* paths are independent only when *M*=2.

Theorem 1. The end-to-end outage of optimal routing when M=2 is given by

$$P_{out}^{opt} = \left(1-\exp\left(-\frac{2\gamma_{th}}{\gamma_0}\right)\right)^L \quad (3)$$

Proof: When *M*=2, all the *W*=*L* paths are independent. Therefore, (2) can be further written as

$$P_{out}^{opt} = P\left(\max_{i=1,\dots,L}\min\left\{\gamma_{S,i,1},\gamma_{i,D,2}\right\}<\gamma_{th}\right) = \prod_{i=1}^{L}P\left(\gamma_{\min}^{(i)}<\gamma_{th}\right) \quad (4)$$

where $\gamma_{\min}^{(i)} = \min\left\{\gamma_{S,i,1},\gamma_{i,D,2}\right\}$, *i*=1,…, *L*. For all *i*, $\gamma_{S,i,1}$ and $\gamma_{i,D,2}$ are i.i.d. exponential random variables. Then

$$P\left(\gamma_{\min}^{(i)}<\gamma_{th}\right) = 1-\exp\left(-\frac{2\gamma_{th}}{\gamma_0}\right) \quad (5)$$

and by substituting (5) into (4), (3) is obtained. ■

From Theorem 1 we can see that $P_{out}^{opt} \approx \left(2\gamma_{th}/\gamma_0\right)^L$ at high SNR. Obviously the full diversity order L can be achieved by optimal routing in a two-hop network.

When M>2, some of the paths are dependent, i.e., a certain link may be shared by multiple paths. Let ϖ_i denote the bottleneck hop of path i, i.e., $\gamma_{r_{\varpi_i-1}^{(i)}, r_{\varpi_i}^{(i)}, \varpi_i} \le \gamma_{r_{k-1}^{(i)}, r_k^{(i)}, k}$, k=1,…, M. We may have $\gamma_{r_{\varpi_i-1}^{(i)}, r_{\varpi_i}^{(i)}, \varpi_i} = \gamma_{r_{\varpi_j-1}^{(j)}, r_{\varpi_j}^{(j)}, \varpi_j}$, when $i \ne j$. This implies that path i and path j share the same bottleneck link. Let $\Upsilon = \left\{\gamma_{r_{\varpi_i-1}^{(i)}, r_{\varpi_i}^{(i)}, \varpi_i}, i = 1,...,W\right\}$, and X represent the number of distinct elements of Υ. Obviously we have $L \le X \le W$.

Lemma 1. Given X, the end-to-end outage of optimal routing is upper bounded by $\left(\gamma_{th}/\gamma_0\right)^X$.

Proof: From (3) we know that

$$\begin{aligned} P_{out}^{opt} &= P\left(\gamma_{r_{\varpi_i-1}^{(i)}, r_{\varpi_i}^{(i)}, \varpi_i} \le \gamma_{r_{k-1}^{(i)}, r_k^{(i)}, k}, \gamma_{r_{\varpi_i-1}^{(i)}, r_{\varpi_i}^{(i)}, \varpi_i} < \gamma_{th}, k = 1,...,M, i = 1,...,W\right) \\ &< P\left(\gamma_{r_{\varpi_i-1}^{(i)}, r_{\varpi_i}^{(i)}, \varpi_i} < \gamma_{th}, i = 1,...,W\right) \end{aligned} \tag{6}$$

Because there are X distinct elements in Υ, it can be further obtained that

$$P_{out}^{opt} < P\left(\gamma_{r_{\varpi_i-1}^{(i)}, r_{\varpi_i}^{(i)}, \varpi_i} < \gamma_{th}\right)^X = \left(1 - \exp\left(-\gamma_{th}/\gamma_0\right)\right)^X \tag{7}$$

For high SNR, the upper bound provided in (7) is approximated by $\left(\gamma_{th}/\gamma_0\right)^X$. ■

Theorem 2. The end-to-end outage of optimal routing when M>2 is given by

$$P_{out}^{opt} = 2\left(1 - \exp\left(-\frac{\gamma_{th}}{\gamma_0}\right)\right)^L - \left(1 - \exp\left(-\frac{\gamma_{th}}{\gamma_0}\right)\right)^{2L} + o\left(\left(\frac{\gamma_{th}}{\gamma_0}\right)^L\right) \tag{8}$$

where $o(x)$ *means the remaining terms are small and approach zero.*

Proof: Rewrite (2) as

$$\begin{aligned} P_{out}^{opt} &= P\left(\max_{i=1,...,W} \min_{k=1,...,M} \left\{\gamma_{r_{k-1}^{(i)}, r_k^{(i)}, k}\right\} < \gamma_{th}, \max_{t=1,...,L} \left\{\gamma_{S,t,1}\right\} < \gamma_{th}\right) \\ &+ P\left(\max_{i=1,...,W} \min_{k=1,...,M} \left\{\gamma_{r_{k-1}^{(i)}, r_k^{(i)}, k}\right\} < \gamma_{th}, \max_{t=1,...,L} \left\{\gamma_{S,t,1}\right\} > \gamma_{th}, \max_{t=1,...,L} \left\{\gamma_{t,D,M}\right\} < \gamma_{th}\right) \\ &+ P\left(\max_{i=1,...,W} \min_{k=1,...,M} \left\{\gamma_{r_{k-1}^{(i)}, r_k^{(i)}, k}\right\} < \gamma_{th}, \max_{t=1,...,L} \left\{\gamma_{S,t,1}\right\} > \gamma_{th}, \max_{t=1,...,L} \left\{\gamma_{t,D,M}\right\} > \gamma_{th}\right) \end{aligned} \tag{9}$$

The L links at the first hop are shared by all W paths, i.e., each is shared by L^{M-2} paths. Therefore, the first term in (9) is equal to

$$P_1 = P\left(\max_{t=1,...,L} \left\{\gamma_{S,t,1}\right\} < \gamma_{th}\right), \tag{10}$$

because all paths are in outage with probability 1 if the SNRs of all L links at the first hop, $\gamma_{S,t,1}$, t=1,…, L, are less than the threshold γ_{th}. Similarly, the L links at the last hop are also shared by all W paths. Considering that the L links at the last hop are independent of the L links at the first hop, the second term in (9) is given by

$$P_2 = P\left(\max_{t=1,...,L} \left\{\gamma_{t,D,M}\right\} < \gamma_{th}\right) P\left(\max_{t=1,...,L} \left\{\gamma_{S,t,1}\right\} > \gamma_{th}\right). \tag{11}$$

It is difficult to derive the exact expression for the third term in (9). However, it can be proved that in this case the number of distinct bottleneck links X must be larger than L. According to Lemma 1, the third term in (9) can be then written as

$$P_3 = o\left(\left(\frac{\gamma_{th}}{\gamma_0}\right)^L\right). \tag{12}$$

Substituting (10-12) into (9), (8) is obtained. ■

Combining Theorems 1 and 2, it can be seen that optimal routing can always achieve full diversity gain. For high SNR, the outage performance remains constant with an increase in the number of hops. However, compared to the case with M=2, a power gain of 2^{L-1} can be achieved when M>2.

B. Ad-hoc Routing

The end-to-end outage is minimized with optimal routing. However, it requires the channel information of all $(M-2)L^2+2L$ links and a joint optimization of all L^{M-1} paths. With a large L or M, this will incur a huge amount of information feedback and a high complexity level. To reduce the amount of required information, in this subsection, we propose an ad-hoc routing strategy, where the relay selection is performed on a per-hop basis. In particular, at hop k=1,…, M-2, the relay with the highest $\gamma_{r_{k-1}^*, j, k}$ is selected, i.e., $r_k^* = \arg\max_{j=1,...,L} \left\{\gamma_{r_{k-1}^*, j, k}\right\}$, where r_{k-1}^* is the relay chosen at hop k-1 (let r_0^*=S). At hop M-1, instead of selecting the one with the largest $\gamma_{r_{M-2}^*, j, k}$, a joint selection should be performed, i.e., $r_{M-1}^* = \arg\max_{j=1,...,L} \min\left(\gamma_{r_{M-2}^*, j, M-1}, \gamma_{j,D,M}\right)$. We will show that in this way full diversity gain can be achieved. The details of ad-hoc routing are summarized below.

Ad-hoc Routing:

Given L and M, let r_k^* denote the index of the relay node selected at the k-th hop, k=1,…, M-1.

Initialization: r_0^*=S.

Recursion:

For k=1: M-2

$r_k^* = \arg\max_{j=1,...,L} \left\{\gamma_{r_{k-1}^*, j, k}\right\}$

End loop

$r_{M-1}^* = \arg\max_{j=1,...,L} \min\left(\gamma_{r_{M-2}^*, j, M-1}, \gamma_{j,D,M}\right)$.

Output the optimal path $\{r_k^*\}$.

Theorem 3. For high SNR, the end-to-end outage of ad-hoc routing is approximated by

$$P_{out}^{ad} \approx (M - 2 + 2^L)\left(\frac{\gamma_{th}}{\gamma_0}\right)^L \tag{13}$$

Proof: In ad-hoc routing, the relay selection of each hop is independent of each other. Therefore, the end-to-end outage can be written as

$$P_{out}^{ad} = 1 - \prod_{i=1}^{M-1}(1 - P_{out,i}^{ad}) \approx \sum_{i=1}^{M-1} P_{out,i}^{ad} \tag{14}$$

where $P_{out,i}^{ad}$ is the outage probability of the i-th hop, i=1,…, M-1. The final approximation is coming from the fact that

$P^{ad}_{out,i}P^{ad}_{out,j}$, $i \neq j$ are too small compared to $P^{ad}_{out,i}$, so we can neglect them. It can be easily obtained that

$$P^{ad}_{out,i} = \begin{cases} \left(1-\exp(-\frac{\gamma_{th}}{\gamma_0})\right)^L, & i=1,...,M-2 \\ \left(1-\exp\left(-\frac{2\gamma_{th}}{\gamma_0}\right)\right)^L, & i=M-1 \end{cases} \quad (15)$$

Substituting (15) into (14) and applying the high SNR approximation, (13) is obtained. ■

From Theorem 3 it can be seen that ad-hoc routing can also achieve full diversity gain. However, in contrast to optimal routing, the outage of ad-hoc routing increases linearly with the number of hops, *M*.

C. N-hop Routing

Ad-hoc routing can be easily implemented in a distributed way because the routing is performed in a per-hop manner and only *L*-link information is required at each hop. However, compared to optimal routing, the performance loss increases with the number of hops. To achieve a better tradeoff between performance and complexity, *N*-hop routing is proposed. In particular, the optimal path is selected every *N* hops, i.e., $ind^*_j = \max_{i=1,...,w_j} \min_{k=(j-1)N+1,...,jN} \left\{\gamma_{r^{(i)}_{k-1},r^{(i)}_k,k}\right\}$, where w_j is the number of paths at the *j*-th step, $j=1,...,\lceil M/N \rceil$. Notice that $r^{(i)}_{(j-1)N} = r^{(ind^*_{j-1})}_{(j-1)N}$, *i*=1,…, w_j, where $r^{(ind^*_{j-1})}_{(j-1)N}$ is the last relay on the path ind^*_{j-1}. The details of *N* hop routing are presented below.

N-hop Routing:

> Given *L*, *M* and *N*, let $T=\lceil M/N \rceil$.
> *Initialization:*
> $r^{(i)}_0$=*S* and $r^{(i)}_M$=*D*, $\forall$ *i*.
> *Recursion:*
> For *j*=1 : *T*
> Generate all the w_j paths;
> $ind^*_j = \arg\max_{i=1,...,w_j} \min_{k=(j-1)N+1,...,jN} \left\{\gamma_{r^{(i)}_{k-1},r^{(i)}_k,k}\right\}$, $r^{(i)}_{(j-1)N} = r^{(ind^*_{j-1})}_{(j-1)N}$;
> $R^*_j = \{r^{(ind^*_j)}_k\}$, *k* = (*j*-1)*N*+1,…, min (*jN*, *M*).
> End loop
> Output the optimal path $\{R^*_1,...,R^*_T\}$.

Theorem 4. For high SNR, the end-to-end outage of N-hop routing is approximated by

$$P^{N-hop}_{out} \approx \begin{cases} (T-1+2^L)\left(\frac{\gamma_{th}}{\gamma_0}\right)^L & if\ M-(T-1)N=2 \\ (T+1)\left(\frac{\gamma_{th}}{\gamma_0}\right)^L & otherwise \end{cases} \quad (16)$$

where $T=\lceil M/N \rceil$.*

Proof: The end-to-end outage of *N*-hop routing can be written as

$$P^{N-hop}_{out} = 1-\prod_{i=1}^{T}\left(1-P^{N-hop}_{out,i}\right) \approx \sum_{i=1}^{T} P^{N-hop}_{out,i} \quad (17)$$

where $P^{N-hop}_{out,i}$ is the outage at the *i*-th step. And the final approximation follows the same argument as (14).

For *i*=1,…, *T*-1, the optimal path is selected in an *N*-hop subnetwork (notice that at the *N*-th hop there are *L* relay nodes in total, instead of one destination node). Following a similar derivation to optimal routing, the outage at the *i*-th step can be obtained as

$$P^{N-hop}_{out,i} = \left(1-\exp\left(-\frac{\gamma_{th}}{\gamma_0}\right)\right)^L,\ i=1,...,T-1. \quad (18)$$

Theorems 1 and 2 can be applied to the last step, i.e., *i*=*T*, and we have

$$P^{N-hop}_{out,T} = \begin{cases} \left(1-\exp\left(-\frac{2\gamma_{th}}{\gamma_0}\right)\right)^L & if\ M-(T-1)N=2 \\ 2\left(1-\exp\left(-\frac{\gamma_{th}}{\gamma_0}\right)\right)^L + o\left(\left(\frac{\gamma_{th}}{\gamma_0}\right)^L\right) & otherwise \end{cases} \quad (19)$$

Combining (17)-(19) and applying the high SNR approximation, (16) is obtained. ■

From Theorem 4 it can be seen that *N*-hop routing also achieves full diversity gain, and the outage increases linearly with *T*. When *T*=1, *N*-hop routing reduces to optimal routing. With an increase in *T* (or a decrease in *N*), the performance gradually deteriorates and becomes close to that of ad-hoc routing. An appropriate *N* should be selected to achieve a good performance-complexity tradeoff. At this time, *N* is determined through simulations. An analytical approach is the subject of current research.

IV. SIMULATION RESULTS

In this section, we present simulation results that validate the previous analysis. Consider a multihop network with *M* hops and *L* relays at each hop. To determine the SNR threshold γ_{th}, we follow a similar argument as in [14], that is, the SNR threshold is set as $\gamma_{th}=2^r-1$, where *r* is the rate. In this paper, we assume *r*=2 bit/s/Hz and so γ_{th}=3.

Fig. 2 presents the theoretical and simulation results for the end-to-end outage performance of optimal routing with different values of *M* and *L*=2 relays at each hop. The outage expression for optimal routing in a 2-hop network has been presented in Theorem 1. When *M*>2, Theorem 2 provides a high-SNR approximation. Both have been verified by the simulation results. As shown in Fig. 1, a perfect match can be observed in both cases.

As demonstrated in Section III, optimal routing always achieves full diversity gain (*L*-fold), regardless of *M*. This has been clearly shown in Fig. 1. However, the value of *M* does affect the power gain. On one hand, the increase of *M* will lead to a higher outage on each path. On the other hand, the overall outage can be improved because there are more possible paths available, although they are correlated. Comparing (3) and (8) we can see that for high SNR, a power gain of 2^{L-1} can be achieved when *M*>2. That is why a 1-dB gap is observed at the outage of 10^{-2} in Fig. 1 between the curve with *M*=2 and the one

* An appropriate *N* should be chosen to ensure that $M-(T-1)N \geq 2$.

with M=4 or 8. For low SNR, the increase of M will lead to an increase in outage. From (8) it can be seen that the third item significantly contributes to the overall outage with a small value of SNR; this will increase with M because there will be more distinct paths.

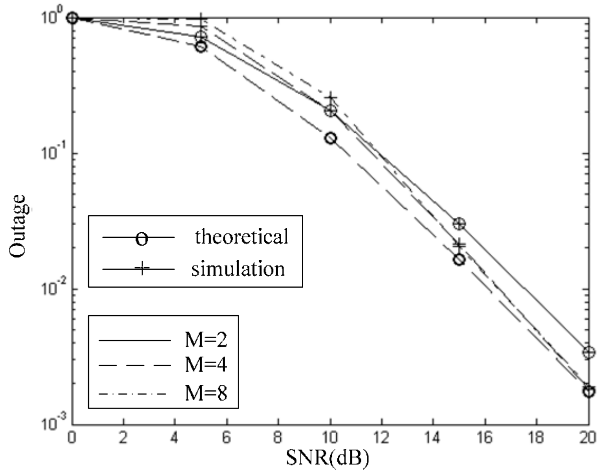

Fig. 2: Outage performance of optimal routing with different M. (L=2).

Fig. 3 shows the outage performance of optimal routing for different values of L. Clearly, optimal routing can always achieve full diversity gain, and the performance gap between M=2 and M=4 is larger with an increase in L. This is because a power gain of 2^{L-1} is achieved when M>2 at high SNR as shown in Section III.

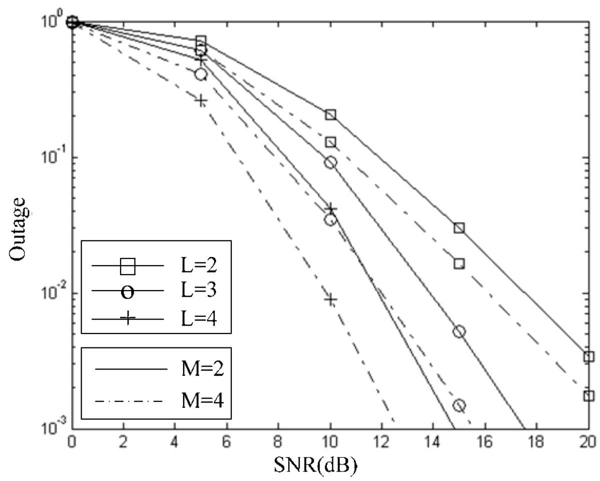

Fig. 3: Outage performance of optimal routing with different values of L. M=2 or 4 hops.

Fig. 4 presents the outage comparison of optimal routing, ad-hoc routing, and N-hop routing in a 4-hop network. With N-hop routing, the best path is selected every N=2 hops. It can be seen that all three routing strategies can achieve full diversity gain. However, a 2-dB power gain is observed with optimal routing at an outage of 10^{-2} when L=2, and this gain will further increase to 3-dB when L=3. The outage performance of N-hop routing is similar to that of ad-hoc routing. Actually from Theorem 3 and 4 we know that the power gain difference of these two strategies is $(2+2^L)/(1+2^L)$ when M=4 and N=2, which is very small and will diminish further with L increasing.

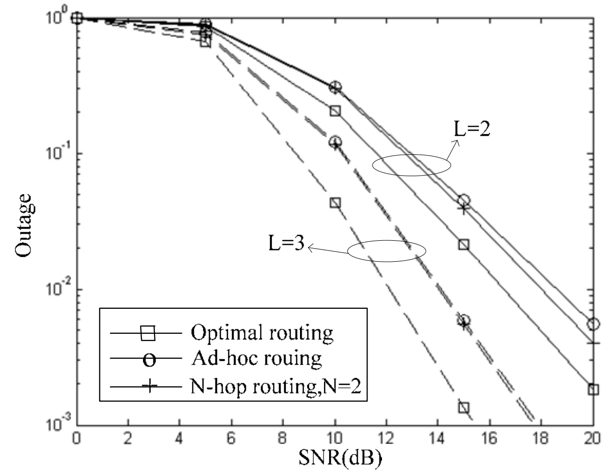

Fig. 4: Outage performance of optimal routing, ad-hoc routing and N-hop routing with different values of L. M=4 hops.

With an increase in M, the performance gain of N-hop routing over ad-hoc routing is clearly observed. As shown in Fig. 5, in an 8-hop network, the performance gaps of these three routing strategies are increased compared to the 4-hop case. For example, 3-dB and 2-dB gains can be achieved by optimal routing and N-hop routing (N=4) over ad-hoc routing at an outage of 10^{-2}, respectively. For N-hop routing, the performance is greatly improved with an increase in N; however, the required information and complexity level also increase.

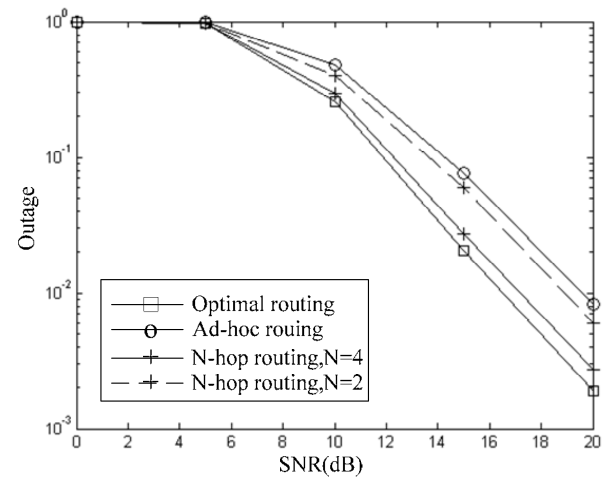

Fig. 5: Outage performance of optimal routing, ad-hoc routing and N-hop routing. M=8 hops and L=2.

Fig. 6 shows the effect of the number of hops, M, on the outage performance of the three routing strategies. Clearly, optimal routing maintains the same outage performance with an increase in M, as was demonstrated in Fig. 2. However, the performance of both ad-hoc and N-hop routing deteriorates. As (13) and (16) shows, the end-to-end outage probability of both routing strategies increase with M.

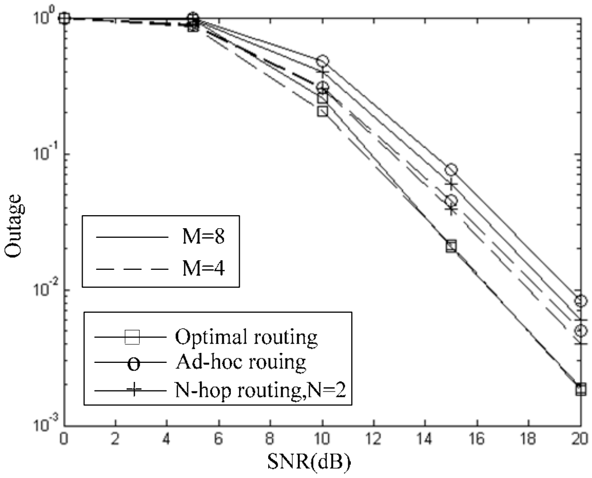

Fig. 6: Outage performance of optimal routing, ad-hoc routing and *N*-hop routing with different values of *M*. L=2.

So far we have shown that in an *M*-hop network with *L* relays at each hop, all three proposed routing strategies can achieve full diversity gain. However, the power gain is different. The performance gap between optimal routing and ad-hoc routing (or *N*-hop routing) increases with the number of hops, *M*, and the performance of *N*-hop routing can be significantly improved with an increase in *N*.

Despite its superior performance, optimal routing needs to collect the information of all $2L+(M-2)L^2$ links and compare all L^{M-1} paths to find the optimal one. With a large number of relays or hops, optimal routing would require a huge amount of information feedback and incur high complexity, which makes it impractical for large-scale networks. In contrast, ad-hoc routing only requires the information of *L* links at each hop ($2L$ at the joint selection of the last two hops) and ML total comparisons to perform the routing. Because the relays (or say, paths) are selected hop by hop, it can easily be implemented in a distributed way. *N*-hop routing is a tradeoff between optimal routing and ad-hoc routing. It requires the information of $L+(N-1)L^2$ links ($2L+(N-2)L^2$ at the last step) and NL^{N-1} comparisons at each step. When the number of hops, *M*, is large, an appropriate *N* could be selected to achieve a good performance-complexity tradeoff.

It should also be noted that despite an increasing performance gap compared to the optimal strategy, only a slight loss is occurred by ad-hoc routing when *M* is small. This makes ad-hoc routing highly attractive in infrastructure-based multihop networks where the number of hops usually not large.

V. CONCLUSIONS

In this paper, we investigated routing strategies for an *M*-hop network with *L* relays at each hop, with a goal of minimizing the end-to-end outage. We demonstrated that optimal routing can achieve full diversity order, and the performance does not deteriorate when the number of hops, *M*, increases. This is because more paths are available with a larger *M*, although for each path the outage probability increases with *M*. Despite its superior performance, optimal routing requires the channel state information of all the links and a joint optimization over L^{M-1} paths. To reduce the amount of information and the complexity level, ad-hoc routing was proposed, where the relay selection is performed in a per-hop manner. Only *L*-link information is needed at each hop, and *ML* comparisons to perform the routing. It was shown that ad-hoc routing can also achieve full diversity gain. However, the performance gap between optimal routing and ad-hoc routing increases with the number of hops. To achieve a good performance-complexity tradeoff, N-hop routing was proposed, where a joint optimization is performed every N hops. The outage analysis of these three routing strategies was verified by simulation results.

Much remains to be investigated. The analysis of the performance loss and complexity of N-hop routing compared to optimal routing is meaningful for the proper choice of *N*. Also, an extension of these three routing algorithms to broadband systems will be pursued.

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