# 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 synthesize routing issue and cooperative diversity with the consideration of a realistic channel model. 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 ad-hoc routing performs worse than optimal routing, especially with a large 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 provided which verify the outage analysis of the proposed routing strategies.

**Index Terms**

Routing, Diversity gain, Cooperative networks, Multihop, Selective relaying.

This paper was presented in part at the IEEE WCNC 2007, Hong Kong, Mar. 2007.

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This material is based on research sponsored by the Air Force Research Laboratory, under agreement number FA9550-06-1-0077. 

# I. INTRODUCTION

Recently, multihop wireless networks, either infrastructure-based or ad hoc (for example, see [1]-[2] and the references therein), have attracted much attention. Many routing protocols have been proposed, such as Dynamic Source Routing (DSR) [3], Ad hoc On Demand Distance Vector (AODV) [4] and Destination-Sequenced Distance Vector (DSDV) [5]. In most of these works, a deterministic 'disk model' is assumed, where the information is successfully received if the distance between the source node and the destination node is within a specified value, regardless of the real channel conditions. Then, the entire network is modeled as a graph, and routing protocols are developed based on point-to-point error-free links aiming at the shortest path or the minimum number of hops (see [6]-[8] for surveys). In these works, two fundamental properties of wireless networks have often been ignored: 1) the variable quality of wireless channels, which means an unpredictable radio range; 2) and the broadcast nature of wireless transmissions. As pointed out in [9]-[10] and demonstrated experimentally in [11]-[13], the wireless channel changes rapidly with time, and thus, a 'disk model' is not accurate for wireless networks. The stochastic nature of the fading channel and the fact that the signal-to-noise ratio (SNR) is a random variable cannot be neglected. Also, several researchers have confirmed that minimum-hop routing might lead to a path that uses longer range links of marginal quality [14]-[15]. Therefore, in most wireless applications, the routing protocols developed for wired networks will not perform well.

In the wireless physical layer, 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 [16]-[18].

Although there has been a significant effort on the study of cooperative systems, there has been very little work on the cross-layer design of such systems, especially on combining cooperation and routing. In [19], the problem of power allocations among transmitting nodes in a *pre-selected* route to maximize the network lifetime is investigated. The joint optimization of routing and power allocation is addressed in [20]-[22], either with relay-cluster-based cooperation [20] or multihop cooperation [21]-[22]. In these works, however, the communications overhead and algorithmic complexity are not considered. The work in [23] explores the benefits of cooperative communications in the networking context at different protocol layers. Distributed space-time block code is used at the physical layer to facilitate cooperation among relay nodes. Through cooperative transmission, significant throughput enhancement can be observed at the expense of high energy consumption. How to reduce the energy penalty, which mainly comes from the overhead communications among relay nodes to coordinate the transmission, and how to deal with the multiple frequency and time offsets incurred by simultaneously transmitting from distributed relay nodes are challenging problems. In [24] the cooperative transport of packets is integrated in a proposed new architecture for next-generation mobile ad hoc networks . As pointed out in [24], selecting relay nodes with as little overhead as possible is a key problem in cooperative transport.

In this paper, we employ a realistic channel model (including path loss and Rayleigh fading) and the end-to-end outage as the performance metric to investigate the routing issue from a link-layer point of view. We mainly focus on the relay (or path) selection from the source node to the destination node with limited communications overhead. We consider a multihop network with multiple relays at each hop and aim at minimizing the end-to-end (or source-to-destination) outage. To simplify the analysis and obtain some insights, we consider a one-dimensional linear network model. In particular, a generalized linear network with randomly located relay clusters and an idealized linear network with equally spaced relay clusters are both considered. The nodes within the same cluster are closely spaced and cooperate in signal transmission and reception. In the network, only one path is active for a source-destination pair. This type of linear model has been used in [20]-[22],[25]-[28].

Routing strategies are designed to fully exploit the diversity gain provided by the cooperation among relays with different amounts of communications overhead and with different algorithmic complexity. 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 (CSI) 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 [‡]

[‡]The $L$ channels from the transmitting node to the receiving nodes are referred to as $L$-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 order is $L$ 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 power gains are different. For optimal routing, the power gain is only determined by the variances of the channel gains of the first and the last hop. The power gain of ad hoc routing, however, is related to the variances of the channel gains of each hop. For $N$-hop routing, the power gain is determined by the variances of the channel gains of hop $iN+1$, $i = 0, 1, ..., \lfloor M/N \rfloor$, and hop $M$. Hence, for the idealized linear network, where each hop has the same average channel power gain, 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 an optimal routing strategy and analyze the end-to-end outage performance. Ad-hoc routing and N-hop routing are proposed and analyzed in Sections IV and V, respectively. A comparison of these strategies is given in Section VI. Finally, Section VII summarizes and concludes the paper.

## II. SYSTEM MODEL

We consider a generalized $M$-hop linear network model, where $M-1$ relay clusters are randomly located from the source node to the destination node. Each relay cluster includes $L$ relay nodes. We assume that the distance between relay clusters is much larger than the distance between the nodes in any one cluster. Therefore, the channel gains of a specific hop are independent and identical distribution. Also, we assume that each node is equipped with only one antenna. A special case of this generalized linear network model, when the $M-1$ relay clusters are equally spaced from the source to the destination, is shown in Fig. 1. We refer this model as the idealized linear network model.

We first consider TDMA without spatial reuse, that is, there is only one transmission during any particular time period. The spatial reuse issue will be considered in Section VI-C. No interference cancellation is adopted; we treat the interference, moreover, as Gaussian noise.

A *selective* decode-and-forward relaying strategy is assumed; in particular, at each hop, only one relay node is selected to forward the packet. The selected relay node will fully decode the received packet, re-encode it, and then forward it to the next relay cluster. Although exploiting all the signals transmitted by multiple previous hops can greatly improve the energy-efficiency [25]-[26], here, we assume that a specific receiving node only uses the signal transmitted by its neighboring relay cluster. This approach allows us to concentrate on the design and comparisons of the routing strategies, and the results developed here can be easily combined with the techniques in [25]-[26].

The channel gain of hop $m$ is modeled as a complex Gaussian random variable with zero mean and variance $\sigma_m^2/2$ per complex dimension. In general, this includes path loss, shadowing, and Rayleigh fading. We assume the channel variations are slow compared to the length of a packet. We also assume each node has the same transmitting power $P_T$, and the variance of the additive white Gaussian noise is $N_0/2$ per complex dimension. With a finite bandwidth $B$ Hz, the SNR averaged over the Rayleigh fading and ignoring path loss and shadowing, can be defined as

$$\gamma_0 = \frac{P_T}{BN_0} \tag{1}$$

Including the path loss and shadowing, then, the average SNR of the channels at hop $m$ at the receiver is given by

$$\overline{\gamma}_m = \sigma_m^2 \gamma_0 \tag{2}$$

where $\sigma_m^2$ results from the attenuation with distance and shadowing. Let $\gamma_{i,j,m}$ represent the SNR of the channel from relay $i$ to relay $j$ at hop $m$, $i, j = 1, ..., L$ and $m = 2, ..., M-1$. $\gamma_{S,j,1}$ and $\gamma_{i,D,M}$, $j = 1, ..., L$, are the SNRs at hops $1$ and $M$, respectively; thus, we have $(M-2)L^2 + 2L$ 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 $r_m^{(i)}$ represent the relay node at hop $m$ in path $i$, $i = 1, ..., W$ and $m = 1, ..., M-1$. Let $r_0^{(i)}$ denote the source node and $r_M^{(i)}$ denote the destination node. Obviously each path has a different relay set $\mathbf{r^{(i)}} = \{r_m^{(i)}\}$ and the corresponding SNR set is given by $\{\gamma_{r_{m-1}^{(i)},r_m^{(i)},m}\}$. 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 $\mathbf{r}=\{1,2,L,...,L-1\}$.

Here, we focus on the end-to-end outage performance. In particular, the outage of path $i$, $i=1,...,W$, is given by

$$\begin{aligned} P_{out}^{(i)} &= 1-\prod_{m=1}^{M}\left(1-P_{out,m}^{(i)}\right)=1-\prod_{m=1}^{M}\left(1-\Pr\left[\gamma_{r_{m-1}^{(i)},r_m^{(i)},m}<\gamma_{th}^{M}\right]\right) \\ &= \Pr\left[\min_{m=1,...,M}\left\{\gamma_{r_{m-1}^{(i)},r_m^{(i)},m}\right\}<\gamma_{th}^{M}\right] \end{aligned} \tag{3}$$

where $P_{out,m}^{(i)}$ is the outage probability at hop $m$ of path $i$. $\gamma_{th}^{M}$ represents the required SNR threshold and it can be written as

$$\gamma_{th}^{M}=\rho*(2^{M\Psi_{req}}-1). \tag{4}$$

The parameter $\rho$ ranges from 1 to about 6.4, depending on the degree of coding used [29]; and $\Psi_{req}$ is the required end-to-end rate in bits/s/Hz. For multihop path $i$, the instantaneous end-to-end rate is the minimum rate of the $M$ hops [27], that is,

$$\Psi_i=\min_{m=1,...,M}\frac{1}{M}\log_2(1+\frac{\gamma_{r_{m-1}^{(i)},r_m^{(i)},m}}{\rho}) \tag{5}$$

We can see that the outage probability is also the probability that the instantaneous end-to-end rate is smaller than the required end-to-end rate. Obviously, the end-to-end outage of an $M$-hop path is limited by the worst hop.

## III. Optimal routing strategy

In this section, we first discuss the optimal routing strategy and its outage behavior. Then, we present simulation results to verify the theoretical analysis.

### *A. Routing Algorithm and Outage Analysis*

As shown in (3), the end-to-end outage of path $i$ is limited by the minimum SNR of $M$ hops, $\gamma_{\min}^{(i)}=\min_{m=1,...,M}\left\{\gamma_{r_{m-1}^{(i)},r_m^{(i)},m}\right\}$. Therefore, to minimize the end-to-end outage of the network, the path with the maximum $\gamma_{\min}^{(i)}$ should be chosen. In the optimal routing strategy, we first find the minimum SNR of each path, and then compare these minimum SNRs and choose the path with the largest minimum SNR. The details are provided below.

*Optimal Routing:*

Given $L$ and $M$, let $W = L^{M-1}$.

*Initialization*:

Generate all possible paths $\{r_m^{(i)}\}$, $r_0^{(i)} = S$ , $r_M^{(i)} = D$, $i = 1, ..., W$.

$\gamma_{min}^{max} = 0$, $ind^* = 0$.

*Recursion*:

For $i = 1 : W$

Calculate $\gamma_{\min}^{(i)} = \min\limits_{m=1,...,M} \left\{ \gamma_{r_{m-1}^{(i)}, r_m^{(i)}, m} \right\}$ 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 $\{r_m^{(ind^*)}\}$.

The end-to-end outage occurs when the $W$ possible paths are all in outage, that is, the largest minimum SNR is below the SNR threshold. Hence, the end-to-end outage of optimal routing is given by

$$P_{out}^{opt} = \Pr \left[ \max_{i=1,...,W} \min_{m=1,...,M} \left\{ \gamma_{r_{m-1}^{(i)}, r_m^{(i)}, m} \right\} < \gamma_{th}^M \right] \tag{6}$$

It is not trivial to solve (6) 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 $\gamma_{2,D,4}$. 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*

$$P_{out}^{opt} = \left( 1 - \exp \left( - \frac{(\sigma_1^2 + \sigma_2^2)\gamma_{th}^M}{(\sigma_1^2 \sigma_2^2)\gamma_0} \right) \right)^L \tag{7}$$

*Proof:* When $M = 2$, all the $W = L$ paths are independent. Therefore, (6) can be further written as

$$P_{out}^{opt} = \Pr \left[ \max_{i=1,...,L} \min\{\gamma_{S,i,1}, \gamma_{i,D,2}\} < \gamma_{th}^M \right] = \prod_{i=1}^{L} \Pr \left[ \gamma_{min}^{(i)} < \gamma_{th}^M \right] \tag{8}$$

where $\gamma_{min}^{(i)} = \min\{\gamma_{S,i,1}, \gamma_{i,D,2}\}$, $i = 1, ..., L$. For all $i$, $\gamma_{S,i,1}$ and $\gamma_{i,D,2}$ are independent exponential random variables with mean $\overline{\gamma}_1$ and $\overline{\gamma}_2$, respectively. Then

$$\Pr\left[\gamma_{min}^{(i)} < \gamma_{th}^M\right] = 1 - \exp\left(-\frac{(\overline{\gamma}_1 + \overline{\gamma}_2)\gamma_{th}^M}{\overline{\gamma}_1\overline{\gamma}_2}\right) = 1 - \exp\left(-\frac{(\sigma_1^2 + \sigma_2^2)\gamma_{th}^M}{(\sigma_1^2\sigma_2^2)\gamma_0}\right) \tag{9}$$

And (7) follows easily. ■

From Theorem 1, we can see that $P_{out}^{opt} \approx ((\sigma_1^2 + \sigma_2^2)\gamma_{th}^M/(\sigma_1^2\sigma_2^2)\gamma_0)^L$ for high SNR. Obviously, full diversity-order $L$ can be achieved by optimal routing in a two-hop network.

A special network model is the idealized linear network model, where relay clusters are equally spaced from the source node to the destination node. In this model, we assume that $\sigma_m^2 = 1$, $m = 1, ..., M$. We can easily obtain the following corollary.

*Corollary 1. The end-to-end outage of optimal routing for the idealized linear network model when $M = 2$ is given by*

$$P_{out}^{opt} = \left(1 - \exp\left(-\frac{2\gamma_{th}^M}{\gamma_0}\right)\right)^L \tag{10}$$

When $M > 2$, some of the paths are usually dependent, i.e., a certain link may be shared by multiple paths. Let $\omega_i$ denote the bottleneck hop of path $i$, i.e., $\gamma_{r_{\omega_i-1}^{(i)}, r_{\omega_i}^{(i)}, \omega_i} \leq \gamma_{r_{m-1}^{(i)}, r_m^{(i)}, m}$ , $m = 1, ..., M$. We may have $\gamma_{r_{\omega_i-1}^{(i)}, r_{\omega_i}^{(i)}, \omega_i} = \gamma_{r_{\omega_j-1}^{(j)}, r_{\omega_j}^{(j)}, \omega_j}$, when $i \neq j$ . This implies that path $i$ and path $j$ share the same bottleneck link. Let $\Upsilon = \{\gamma_{r_{\omega_i-1}^{(i)}, r_{\omega_i}^{(i)}, \omega_i}, i = 1, ..., W\}$ and $X$ represent the number of distinct elements of $\Upsilon$.

*Lemma 1. $\Upsilon$ includes at least $L$ distinct links, that is, $X \geq L$; and $X = L$ occurs only when the bottleneck links are either the $L$ links in the first hop or the $L$ links in the last hop.*

*Proof:* Observing the topology of the network, we can see that a link can be shared by at most $L^{M-2}$ paths. In addition, only the links in the first hop and the last hop are shared by $L^{M-2}$ paths. Hence, at least $L$ links are needed to cover all $W = L^{M-1}$ possible paths, that is, $\Upsilon$ includes at least $L$ distinct links, $X \geq L$. $X = L$ occurs only when the bottleneck links are either the $L$ links in the first hop or the $L$ links in the last hop. ■

*Lemma 2. Given X, for high SNR, the end-to-end outage of optimal routing can be upper bounded by $\prod_{j=1}^{X}(1/\sigma_{\varepsilon_j}^2)(\gamma_{th}^M/\gamma_0)^X$, where $\varepsilon_j$ is the hop index of the bottleneck link.*

*Proof:* From (6) we know that

$$\begin{aligned} P_{out}^{opt} &= \Pr\left[\gamma_{r_{\omega_i-1}^{(i)},r_{\omega_i}^{(i)},\omega_i} \leq \gamma_{r_{m-1}^{(i)},r_m^{(i)},m}, \gamma_{r_{\omega_i-1}^{(i)},r_{\omega_i}^{(i)},\omega_i} < \gamma_{th}^M, m=1,...,M, i=1,...,W\right] \\ &< \Pr\left[\gamma_{r_{\omega_i-1}^{(i)},r_{\omega_i}^{(i)},\omega_i} < \gamma_{th}^M, i=1,...,W\right] \end{aligned} \tag{11}$$

Because there are $X$ distinct elements in $\Upsilon$ , it can be further obtained that

$$P_{out}^{opt} < \prod_{j=1}^{X}(1-\exp(-\frac{\gamma_{th}^M}{\sigma_{\varepsilon_j}^2\gamma_0})) \tag{12}$$

where $\varepsilon_j$ is the hop index of the bottleneck link.

For high SNR, the upper bound provided in (12) is approximated by $\prod_{j=1}^{X}(1/\sigma_{\varepsilon_j}^2)(\gamma_{th}^M/\gamma_0)^X$. ■

*Theorem 2. For high SNR, the end-to-end outage of optimal routing when $M > 2$ is given by*

$$\begin{aligned} P_{out}^{opt} \approx &\left(1-\exp\left(-\frac{\gamma_{th}^M}{\sigma_1^2\gamma_0}\right)\right)^L + \left(1-\exp\left(-\frac{\gamma_{th}^M}{\sigma_M^2\gamma_0}\right)\right)^L \\ &- \left(1-\exp\left(-\frac{\gamma_{th}^M}{\sigma_1^2\gamma_0}\right)\right)^L \left(1-\exp\left(-\frac{\gamma_{th}^M}{\sigma_M^2\gamma_0}\right)\right)^L + o\left(\left(\frac{\gamma_{th}^M}{\gamma_0}\right)^L\right) \end{aligned} \tag{13}$$

*Proof:* Rewrite (6) as

$$\begin{aligned} P_{out}^{opt} &= \Pr\left[\max_{i=1,...,W}\min_{m=1,...,M}\left\{\gamma_{r_{m-1}^{(i)},r_m^{(i)},m}\right\} < \gamma_{th}^M, \max_{t=1,...,L}\{\gamma_{S,t,1}\} < \gamma_{th}^M\right] \\ &+\Pr\left[\max_{i=1,...,W}\min_{m=1,...,M}\left\{\gamma_{r_{m-1}^{(i)},r_m^{(i)},m}\right\} < \gamma_{th}^M, \max_{t=1,...,L}\{\gamma_{S,t,1}\} > \gamma_{th}^M, \max_{t=1,...,L}\{\gamma_{t,D,M}\} < \gamma_{th}^M\right] \\ &+\Pr\left[\max_{i=1,...,W}\min_{m=1,...,M}\left\{\gamma_{r_{m-1}^{(i)},r_m^{(i)},m}\right\} < \gamma_{th}^M, \max_{t=1,...,L}\{\gamma_{S,t,1}\} > \gamma_{th}^M, \max_{t=1,...,L}\{\gamma_{t,D,M}\} > \gamma_{th}^M\right] \end{aligned} \tag{14}$$

The $L$ links in the first hop are shared by all $W$ paths, i.e., each is shared by $L^{M-2}$ paths. Therefore, the first term in (14) is equal to

$$P_1 = \Pr\left[\max_{t=1,...,L}\{\gamma_{S,t,1}\} < \gamma_{th}^M\right] \tag{15}$$

because all paths are in outage with probability one if the SNRs of all $L$ links at the first hop, $\gamma_{S,t,1}$ , $t = 1, ..., L$, are less than the threshold $\gamma_{th}^M$. 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 (14) is given by

$$P_2 = \Pr\left[\max_{t=1,...,L}\{\gamma_{t,D,M}\} < \gamma_{th}^M\right]\Pr\left[\max_{t=1,...,L}\{\gamma_{S,t,1}\} > \gamma_{th}^M\right] \tag{16}$$

It is difficult to derive the exact expression for the third term in (14). However, in this case, the links in the first hop and the last hop will not all be in outage. According to Lemma 1, the number of distinct bottleneck links $X$ must be larger than $L$. Then, according to Lemma 2, for high SNR, the third term in (14) can be written as

$$P_3 \approx o\left(\left(\frac{\gamma_{th}^M}{\gamma_0}\right)^L\right) \tag{17}$$

Substituting (15-17) into (14), (13) can be obtained. ■

The following corollary can be proved for the idealized linear network model:

*Corollary 2. For high SNR, the end-to-end outage of optimal routing for the idealized linear network model when $M > 2$ is given by*

$$P_{out}^{opt} \approx 2\left(1 - \exp\left(-\frac{\gamma_{th}^M}{\gamma_0}\right)\right)^L - \left(1 - \exp\left(-\frac{\gamma_{th}^M}{\gamma_0}\right)\right)^{2L} + o\left(\left(\frac{\gamma_{th}^M}{\gamma_0}\right)^L\right) \tag{18}$$

Combining Theorems 1 and 2, it can be seen that optimal routing can always achieve full diversity gain. For high SNR, the outage performance is only related to the variances of the channel gains of the first hop and the last hop, that is, $\sigma_1^2$ and $\sigma_M^2$. Hence, for the idealized linear network, the outage performance remains constant with an increase in the number of hops. However, compared to the case of $M = 2$, a power gain of $2^{L-1}$ can be achieved when $M > 2$.

### B. Simulation Results

In this subsection, we present simulation results to validate the previous analysis. To obtain some insights, we consider the linear network model with equally spaced relay clusters. The target end-to-end throughput of the M-hop network is $2/M$ bit/s/Hz. † We also assume $\rho = 1$. Hence, the SNR threshold $\gamma_{th}^M = 3$.

Fig. 2 presents the end-to-end outage performance of optimal routing for different numbers of hops, $M$, with $L = 2$ relays at each hop; both simulation and theoretical results (that is, using Corollaries 1 and 2) are presented. As demonstrated, the theoretical analysis is verified by the simulation results. As shown in the previous subsection, optimal routing always achieves

†Here, the distance from the source to the destination increases with an increase in $M$. Hence, the end-to-end throughput decreases with an increase in $M$ if M-phase TDMA scheme is adopted.

full diversity gain ($L$-fold), regardless of $M$. This is also demonstrated in Fig. 2. However, the value of $M$ does affect the power gain. On the one hand, an increase in $M$ 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 (10) and (18) we can see that at high SNR, a power gain of $2^{L-1}$ can be achieved when $M > 2$. This is why a 1-dB gap is observed at an outage of $10^{-2}$ in Fig. 2 between the curve with $M = 2$ and the one with $M = 4$ or $8$. For low SNR, an increase in $M$ will lead to an increased outage. From (18) 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. 3 shows the outage performance of optimal routing with different numbers of relays, $L$. Clearly, optimal routing can always achieve full diversity gain, and the performance gap between $M = 2$ and $M = 4$ increases with $L$. This is because a power gain of $2^L - 1$ is achieved when $M > 2$ for high SNR.

### *C. Implementation Issues*

As shown above, the optimal routing can always achieve full diversity. This approach can be used when a central controller is available. The central controller will collect the channel gains on all of the $Q = (M-2)L^2 + 2L$ links and select the path which has the largest bottleneck-link SNR. The optimal path can be found using the Viterbi algorithm. The $L$ relays in each cluster can be treated as $L$ states; the algorithm moves forward to a new set of states (relays in hop $i + 1$ ) by combining the metric (Maxmin SNR values) of a possible previous state (relays in hop $i$ ) with the incremental metric of the transition (channel gains from relays in hop $i$ to relays in hop $i + 1$) and chooses the best. After arriving at the destination, the algorithm will trace back and output the survivor path (optimal path). The total number of comparisons is $2(M - 2)L^2 - (M - 4)L - 1$. The detailed algorithm is described as following:

Let $\gamma_{min}^{i,j}$ indicate the Maxmin SNR of the optimal path to nodes $j$ of relay cluster $i$;

Let $ind_{min}^{i,j}$ indicate the index of the relay node, which is in relay cluster $i-1$, and which is in the optimal path to nodes $j$ of relay cluster $i$;

Find the optimal path

For $i = 1 : M$

  If $i == 1$

    For $j = 1 : L$

      $\gamma_{min}^{1,j} = \gamma_{s,j,1}; \qquad ind_{min}^{1,j} = S;$

    End Loop

  Elseif $1 < i < M$

    For $j = 1 : L$

      $\{\gamma_{min}^{i,j}, ind_{min}^{i,j}\} = \max_{k=1,\ldots,L}\{\min\{\gamma_{min}^{i-1,k}, \gamma_{k,j,i}\}\};$

    End Loop

  Else

    $\{\gamma_{min}^{M,D}, ind_{min}^{M,D}\} = \max_{k=1,\ldots,L}\{\min\{\gamma_{min}^{M-1,k}, \gamma_{k,D,M}\}\};$

End Loop

Trace-back the optimal path

$r_{M-1} = ind_{min}^{M,D};$

For $i = 3 : M$

  $r_{M-i+1} = ind_{min}^{M-i+2, r_{M-i+2}};$

End Loop

Output the optimal path $\{S, r_1, ..., r_{M-1}, D\}$

## IV. Ad-hoc Routing

The end-to-end outage is minimized with optimal routing; however, it requires the CSI 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 significant amount of feedback and a high complexity level. To reduce the amount of required information, in this section, we propose an ad-hoc routing strategy, in which the relay selection is performed in a per-hop manner. We first present the ad-hoc routing algorithm and its outage analysis. Then, we provide simulation results to verify the theoretical analysis.

### A. Routing Algorithm and Outage Analysis

In the first $M-2$ hops, only the best relay is selected to forward the packet in each hop, that is, the relay with the highest received SNR, $\gamma_{r^*_{m-1},j,m}$, is selected. Hence, at hop $m = 1, ..., M-2$, $r^*_m = \arg \max_{j=1,...,L} \{\gamma_{r^*_{m-1},j,m}\}$ , where $r^*_{m-1}$ is the relay chosen at hop $m-1$ (let $r^*_0 = S$). Obviously, $L$-fold diversity gain is achieved at each hop. The last two hops are different. There is only one receiver (the destination node) in the last hop; if the relay node selection of the $(M-1)$-st hop is only based on the channel in the $(M-1)$-st hop, then there is no diversity gain in the last hop. So, a joint selection is needed in the last two hops in order to guarantee $L$-fold diversity gain. At hop $M-1$, instead of selecting the path with the largest $\gamma_{r^*_{M-2},j,m}$, a joint selection should be performed, i.e., $r^*_{M-1} = \arg \max_{j=1,...,L} \min(\gamma_{r^*_{M-2},j,M-1}, \gamma_{j,D,M})$. We will show that in this way the full diversity gain can be achieved. The details are summarized below.

*Ad-hoc Routing:*

Given $L$ and $M$, let $r^*_m$ denote the index of the relay node selected at the $m$-th hop, $m = 1, ..., M-1$.

*Initialization*: $r^*_0 = S$

*Recursion*:

For $m = 1 : M-2$

$r^*_m = \arg \max_{j=1,...,L} \{\gamma_{r^*_{m-1},j,m}\}$;

End loop

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

Output the optimal path $\{r^*_m\}$

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

$$P^{ad}_{out} \approx \left( \sum_{i=1}^{M-2} \frac{1}{\sigma_i^{2L}} + \left( \frac{1}{\sigma^2_{M-1}} + \frac{1}{\sigma^2_M} \right)^L \right) \left( \frac{\gamma^M_{th}}{\gamma_0} \right)^L \tag{19}$$

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

$$P^{ad}_{out} = 1 - \prod_{i=1}^{M-1} (1 - P^{ad}_{out,i}) \approx \sum_{i=1}^{M-1} P^{ad}_{out,i} \tag{20}$$

where $P^{ad}_{out,i}$ is the outage probability in the $i$-th hop, $i = 1, ..., M-1$. The final approximation comes from the fact that the products $P^{ad}_{out,i} P^{ad}_{out,j}$, $i \neq j$, are small compared to $P^{ad}_{out,i}$, and, to first-order, we can ignore them. Then, it is easily shown that

$$P_{out,i}^{ad} = \begin{cases} \left(1 - \exp(-\frac{\gamma_{th}^M}{\sigma_i^2 \gamma_0})\right)^L, & i = 1, ..., M-2 \\ 1 - \exp\left(-\frac{(\sigma_{M-1}^2 + \sigma_M^2)\gamma_{th}^M}{(\sigma_{M-1}^2 \sigma_M^2)\gamma_0}\right)^L, & i = M-1 \end{cases} \tag{21}$$

Substituting (21) into (20) and applying the high-SNR approximation, (19) is obtained. ■

For the idealized linear network, the following corollary is easily proved.

*Corollary 3. For high SNR, the end-to-end outage of ad-hoc routing for the idealized linear network is*

$$P_{out}^{ad} \approx (M - 2 + 2^L) \left(\frac{\gamma_{th}^M}{\gamma_0}\right)^L \tag{22}$$

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 is related to the variances of the channel gains of each hop. For the idealized linear network, this means that the outage performance increases linearly with the number of hops, $M$. Compared with the performance of optimal routing, when $M$ is small, ad-hoc routing has an outage performance that is close to that of optimal routing; the performance gap, however, increases with an increase in the number of hops, $M$.

## *B. Simulation Results*

In this subsection, we present simulation results for ad-hoc routing with different numbers of hops and relays for medium-to-high SNR. The same simulation environment as in Section III-B is adopted. Fig. 4 presents the theoretical and simulation results for the end-to-end outage performance of ad hoc routing with different numbers of hops, $M$, using $L = 2$ relays at each hop; Excellent agreement can be observed for $M = 2$, $4$, and $8$. As demonstrated in the previous subsection, ad-hoc routing always achieves full diversity gain ($L$-fold), regardless of $M$. This has been clearly shown in Fig. 4. The value of $M$ affects the power gain; in particular, the outage increases linearly with an increase in $M$.

Fig. 5 shows the outage performance of ad-hoc routing with different numbers of relays, $L$. Clearly, ad-hoc routing can always achieve full diversity gain. For the same $L$, increasing the number of hops $M$ will linearly increase the outage. An interesting observation is that the performance gap between $M = 4$ and $M = 8$ decreases with an increase in $L$. The reason is that the power gain is $M - 2 + 2^L$, so the term $2^L$ will dominate when we increase the number of relays $L$ in each hop for a fixed $M$.

### C. Implementation Issues

In ad-hoc routing, at each hop the best relay is selected based on the received SNRs, or equivalently, the measured channel gains. It can be implemented in a centralized way or in a distributed way. If a central controller is available (such as a base station in cellular networks or an access point in mesh networks), it can collect all the CSI and then assign the transmission. In the case where a central controller is not available, ad-hoc routing can also be performed in a distributed way. In [30] a distributed relay selection algorithm is proposed where each relay sets a timer based on its measured channel gain. The larger the channel gain is, the shorter the timer should be. In this way, the timer of the relay with the best channel will expire first. That relay then sends a flag signal. All other relays, while waiting for their timer to reduce to zero, are in listening mode. As soon as they hear the flag signal, they back off. This method requires that all the relays can hear each other.

The algorithmic complexity of ad-hoc routing comes from the relay selection at each hop. If it is implemented in a central controller, $L - 1$ comparisons are needed in the first $M - 2$ hops, and the last hop needs $2L - 1$ comparisons. Thus, the total number of comparisons is $M(L - 1) + 1$. Compared with optimal routing, ad-hoc routing is much less complex.

## V. $N$-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 $N$-hop routing, the total $M$ hops are divided into non-overlap groups. Each group includes $N$ hops, and optimal routing is performed in each group.

In this section, we first present the $N$-hop routing algorithm and its outage analysis. Then, we show some simulation results to verify the theoretical analysis. Implementation issues are discussed in the last subsection.

### A. Routing Algorithm and Outage Analysis

In $N$-hop routing, the neighboring $N$ hops are grouped together. The relay nodes in a group exchange their CSI and the optimal routing algorithm is performed in each group to find the best path in this group. In this way, the optimal path is selected every $N$ hops, i.e., $ind_j^* = \max_{i=1,...,w_j} \min_{m=(j-1)N+1,...,jN} \left\{ \gamma_{r_{m-1}^{(i)}, r_m^{(i)}, m} \right\}$, where $w_j$ is the number of paths at the $j$-th step, $j = 1, ..., \lceil M/N \rceil$. Notice that $r_{(j-1)N}^{(i)} = r_{(j-1)N}^{(ind_{j-1}^*)}$ ,$i = 1, ..., w_j$, where $r_{(j-1)N}^{(ind_{j-1}^*)}$ is the last relay on the path $ind_{j-1}^*$. The details are presented below.

*$N$-hop Routing:*

Given $L$,$M$ and $N$, let $T = \lceil M/N \rceil$.

*Initialization*:

$r_0^{(i)} = S$ and $r_M^{(i)} = D$, $\forall i$

*Recursion*:

For $j = 1 : T$

Generate all the $w_j$ paths;

$ind_j^* = \arg\max_{i=1,...,w_j} \min_{m=(j-1)N+1,...,jN} \left\{ \gamma_{r_{m-1}^{(i)}, r_m^{(i)}, m} \right\}$, $r_{(j-1)N}^{(i)} = r_{(j-1)N}^{(ind_{j-1}^*)}$;

$R_j^* = \{ r_m^{(ind_j^*)} \}$, $m = (j-1)N + 1, ..., min(jN, M)$.

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*

$$P_{out}^{N-hop} \approx \begin{cases} \left( \prod_{i=1}^{T-1} \frac{1}{\sigma_{(i-1)N+1}^{2L}} + \left( \frac{1}{\sigma_{M-1}^2} + \frac{1}{\sigma_M^2} \right)^L \right) \left( \frac{\gamma_{th}^M}{\gamma_0} \right)^L & if \quad M - (T-1)N = 2 \\ \left( \prod_{i=1}^{T} \frac{1}{\sigma_{(i-1)N+1}^{2L}} + \frac{1}{\sigma_M^{2L}} \right) \left( \frac{\gamma_{th}^M}{\gamma_0} \right)^L & otherwise \end{cases} \tag{23}$$

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

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

$$P_{out}^{N-hop} = 1 - \prod_{i=1}^{T} \left( 1 - P_{out,i}^{N-hop} \right) \approx \sum_{i=1}^{T} P_{out,i}^{N-hop} \tag{24}$$

where $P_{out,i}^{N-hop}$ is the outage for the $i$-th step. For $i = 1, ..., T-1$, the optimal path is selected in an $N$-hop subnetwork (notice that at the last hop ($N$-th hop) of this subnetwork there are $L$

relay nodes in total, instead of one node (destination node) at the last hop of optimal routing in Sec. III). Following a similar derivation to that for optimal routing, the outage at the $i$-th step can be obtained as

$$P_{out,i}^{N-hop} = \left(1 - \exp\left(-\frac{\gamma_{th}^M}{\sigma_{(i-1)N+1}^2 \gamma_0}\right)\right)^L, i = 1, ..., T-1. \tag{25}$$

Theorems 1 and 2 can be applied to the last step, i.e., $i = T$, if $M - (T-1)N = 2$, giving

$$P_{out,T}^{N-hop} = \left(1 - \exp\left(-\frac{(\sigma_{M-1}^2 + \sigma_M^2)\gamma_{th}^M}{(\sigma_{M-1}^2 \sigma_M^2)\gamma_0}\right)\right)^L \tag{26a}$$

otherwise

$$\begin{aligned} P_{out,T}^{N-hop} = &\left(1 - \exp\left(-\frac{\gamma_{th}^M}{\sigma_{M-N+1}^2 \gamma_0}\right)\right)^L + \left(1 - \exp\left(-\frac{\gamma_{th}^M}{\sigma_M^2 \gamma_0}\right)\right)^L \\ &- \left(1 - \exp\left(-\frac{\gamma_{th}^M}{\sigma_{M-N+1}^2 \gamma_0}\right)\right)^L \left(1 - \exp\left(-\frac{\gamma_{th}^M}{\sigma_M^2 \gamma_0}\right)\right)^L + o\left(\left(\frac{\gamma_{th}^M}{\gamma_0}\right)^L\right) \end{aligned} \tag{26b}$$

Combining (24-26) and applying the high-SNR approximation, (23) is obtained. ■

We can also prove the following corollary.

*Corollary 4. For high SNR, the end-to-end outage of $N$-hop routing for the idealized linear network model is*

$$P_{out}^{N-hop} \approx \begin{cases} \left(T - 1 + 2^L\right) \left(\frac{\gamma_{th}^M}{\gamma_0}\right)^L & if \quad M - (T-1)N = 2 \\ (T+1) \left(\frac{\gamma_{th}^M}{\gamma_0}\right)^L & otherwise \end{cases} \tag{27}$$

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

From Theorem 4 it can be seen that $N$-hop routing also achieves full diversity gain. 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 approaches that of ad-hoc routing.

### *B. Simulation Results*

In this subsection, we first present simulation results to verify the outage analysis. Then, we discuss the effect of the parameters $M, N$, and $L$ on the outage performance. The same simulation environment is adopted as in the simulations for optimal routing and ad-hoc routing.

Fig. 6 presents the end-to-end outage performance of $N$-hop routing for different values of $N$ with $M = 16$ hops and $L = 2$ relays at each hop. Theorem 4 provides a high-SNR approximation of the end-to-end outage. As shown in Fig. 6, a perfect match can be observed for all the $N$ values when the SNR is large. As demonstrated in the previous subsection, $N$-hop routing always achieves full diversity gain ($L$-fold), regardless of $M$ and $N$. This is also clearly observed in Fig. 6. However, the value of $N$ does affect the power gain. The cases with $N = 4$ and $N = 8$ hops outperform the case with $N = 2$ by 1.5-dB and 3-dB, respectively, at the expense of more communication overhead and a more complex path search.

In $N$-hop routing, the number of hops in each group determines the tradeoff between outage performance and algorithmic complexity. Increasing $N$ will improve the outage performance, although more channel information exchange is required and a higher algorithmic complexity is expected. Decreasing $N$ will make the algorithm easier to implement, but the performance will deteriorate. An appropriate $N$ should be selected to achieve a good performance-complexity tradeoff. The following two remarks quantify the performance improvement (or degradation) with an increase (or decrease) in $N$.

*Remark 1: With fixed $L$ and sufficiently large $M$, doubling the value of $N$ will roughly improve the outage performance by $(10/L)log_{10}(2)$ dB and the performance improvement will remain the same with an increase in $M$.* [*]

From Theorem 4, we know that the performance gap between $N = 2$ and $N = 4$ is

$$\Delta\gamma_0 = \frac{10}{L} log_{10}\left(\frac{(M/2) - 1 + 2^L}{(M/4) + 1}\right) \tag{28}$$

and the performance gap between $N$ and $2N$, where $N > 2$, is

$$\Delta\gamma_0 = \frac{10}{L} log_{10}\left(\frac{(M/N) + 1}{(M/2N) + 1}\right) \tag{29}$$

With fixed $L$ and sufficiently large $M$, (28) and (29) can both be approximated by $(10/L)log_{10}2$. Hence, a rough rule-of-thumb is that the performance improves as $(10/L)log_{10}2$ dB with a doubling in the value of $N$; and, this performance improvement is the same for different $M$. Thus, for $L = 2$, doubling the number of hops in each group will improve the performance by $5log_{10}2 = 1.5$ dB. This can be observed in Figs. 6 and 7. In Fig. 6, for $L = 2$, the performance improvements with a doubling in $N$ for $N = 2$ and for $N = 4$ are both 1.5-dB. From Fig. 7,

[*]For convenience, in the following discussion, we assume $N = 2^n$ and $M = 2^m$, where $n$ and $m$ are integers.

we can see that the performance improvements from $N = 2$ to $N = 4$ with $M = 8$ or $M = 16$ are also both 1.5-dB when $L = 2$.

*Remark 2: With fixed $M$ and $N > 2$, the performance improvements when doubling the value of $N$ will decrease with an increase in $L$. For $N = 2$, however, the performance improvements may increase with an increase in $L$.*

From (29), we can see that an increase in $L$ will degrade the performance improvements when doubling $N$ if $N > 2$. For the case of $N = 2$, the performance improvement (28) can be approximated by $10log_{10}2$ dB for fixed $M$ and sufficiently large $L$. In Fig. 7, with $M = 8$, the performance gap between $N = 2$ and $N = 4$ is 1.5-dB for $L = 2$; and it increases to 2.2-dB when $L = 6$. Therefore, there is no need to have more than $4$ hops in a group when $L$ is large because the additional performance improvement is negligible.

### C. Implementation Issues

In $N$-hop routing, the entire network is divided into $T$ groups. In each group, optimal routing is performed. Specifically, in each group, a local central controller will collect all the channel gains in the group, and then the optimal routing algorithm will be performed to find the best path in this group. For the first $T - 1$ group, the channel gains of $L + (N - 1)L^2$ links are required and the number of comparisons in each group is $2(N - 1)L^2 - (N - 2)L - 1$; for the last group, the channel gains of $2L + (N - 2)L^2$ links are required and the number of comparisons is $2(N - 2)L^2 - (N - 4)L - 1$. A good performance and complexity tradeoff is achieved by $N$-hop routing.

## VI. Comparison of Routing Algorithms

In this section, we compare the outage, algorithmic complexity, and communications overhead of optimal, ad-hoc, and N-hop routing for different values of $M, L$, and $N$.

### A. Outage in Idealized Linear Networks

In this subsection, we compare the performance of the three routing strategies in the idealized linear network. In Fig. 8, we present an outage comparison of optimal, ad-hoc, 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 achieve the full diversity gain. Compared to ad-hoc routing, a 2-dB power gain is observed with optimal routing at an outage of $10^{-2}$ when $L = 2$, and this gain increases to 3-dB when $L = 3$. The outage performance of $N$-hop routing is similar to that of ad-hoc routing. From Theorems 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 increasing $L$.

With an increase in $M$, the performance gain of $N$-hop routing over ad-hoc routing can be clearly observed. As shown in Fig. 9, in a $16$-hop network, the performance gaps of these three routing strategies are significantly increased compared to the $4$-hop case. For example, 4.5-dB and 2.5-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 amount of information and complexity level also increase.

Fig. 10 shows the effect of the number of hops, $M$, on the outage performance of these three 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 (22) and (27) show, the end-to-end outage of both routing strategies increase with $M$.

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; the power gain, however, 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 $N$. A rule of thumb is that doubling the value of $N$ will roughly improve the outage performance by $(10/L)log_{10}(2)$ dB. The performance improvement decreases with an increase in $L$ and roughly remains the same as an increase in $M$.

### *B. Outage in Random Networks*

In this subsection, we consider a one-dimensional random network. We assume that the source and the destination are located at (0,0) and (0,$d_{max}$), respectively. The relay clusters are uniformly distributed between the source and the destination. The outage performance is averaged over 500 random network realizations. In the simulation, the noise power is normalized to one and the path-loss exponent $\alpha$ equals four. As in [31], the transmitting power is normalized by $P_{max}$, where $P_{max}$ is the transmit power required, for the source and the destination, to achieve a given spectral efficiency $\Psi_{req}$ in direct transmission without shadow and Rayleigh fading. As shown in Fig. 11, we can make the same conclusions as applied to the idealized linear network. As we have analytically demonstrated, large-scale fading does not change the diversity order. The routing strategies achieve the same diversity order and the power gains are different. In particular, the power gain of optimal routing is only determined by the variances of the channel gains of the first and the last hops. The power gain of ad-hoc routing, however, is related to the variances of the channel gains of each hop. For $N$-hop routing, the power gain is determined by the variances of the channel gains of hop $iN + 1$, $i = 0, 1, ..., \lfloor M/N \rfloor$, and hop $M$.

### *C. Outage with Spatial Reuse*

In this subsection, we adopt spatial reuse to improve the spectral efficiency. In particular, a K-phase TDMA scheme [27],[32], $2 \leq K \leq M$, where two nodes separated by $K$ hops can transmit during the same time slot, is employed. We let $K = 4$ for a $M = 8$ hop idealized linear network. This means that two nodes separated by 4 hops can transmit during the same time slot and they will interfere each other. We compare the performance of three routing strategies with and without spatial reuse. Without spatial reuse, i.e., $K = 8$, only one node is allowed to transmit during any particular time slot. The same target end-to-end throughput is required for these two schemes; hence, $\gamma_{th}^4 = 1$ when $\gamma_{th}^8 = 3$.

As shown in Fig. 12, when the SNR $\gamma_0$ is small, significant performance gains can be achieved by spatial reuse. The reason is that, for small $\gamma_0$, the noise power is much larger than the interference power, i.e., the interference can be ignored. In this case, the three routing strategies all significantly benefit from spatial reuse. As shown in Fig. 12, a 4-dB power gain is obtained by spatial reuse at an outage of $10^{-2}$. We also notice that the relative performance gaps of the three routing strategies are similar with and without spatial reuse. With an increase in $\gamma_0$, the interference power will dominate the signal to noise plus interference ratio. In this case, as expected, the outage will not decrease with an increase in $\gamma_0$, that is, error floors will occur. As shown in Fig. 12, all three strategies suffer from error floors when $\gamma_0 > 20$ dB. Therefore, for large $\gamma_0$, spatial reuse is not a good choice.

### D. Complexity Comparison

Optimal routing has superior performance compared with $N$-hop routing and ad-hoc routing. However, optimal routing requires the CSI of all $2L + (M-2)L^2$ links to find the optimal path. With a large number of relays or hops, optimal routing requires a significant amount of information feedback and incurs high complexity as discussed in Section III; this makes it impractical for large-scale networks. In contrast, ad-hoc routing only requires the CSI of $L$ links at each hop ($2L$ links at the joint selection of the last two hops) and $M(L-1)-1$ comparisons to perform the routing strategy. With $M = 8$ hops and $L = 4$ relays in each hop, the number of comparisons required by ad-hoc routing is $25$, which decreases $86\%$, compared with the $175$ comparisons required by optimal routing. Because the relays (or paths) are selected hop by hop, it can be easily implemented in a decentralized way. $N$-hop routing is a tradeoff between optimal routing and ad-hoc routing. It requires the CSI of $L+(N-1)L^2$ links ($2L+(N-2)L^2$ links at the last step) and the optimal path selection over $N$ hops. With $M = 8$ hops, $L = 4$ relays in each hop, and $N = 2$ hops in each group, the number of comparisons required by $N$-hop routing is $100$, which decreases $43\%$, compared with that of optimal routing. The comparisons of these implementation issues are summarized in Table 1.

## VII. Conclusions

In this paper, we investigated routing strategies in an $M$-hop network with $L$ relays at each hop, with the objective to minimize the end-to-end outage. We demonstrated that optimal routing can achieve full diversity order, and the power gain is only determined by the variances of the channel gains of the first and the last hops. This means that, for an idealized linear network, the performance of optimal routing does not deteriorate when the number of hops, $M$, increases. Despite its superior performance, optimal routing requires the CSI 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, in which the relay selection is performed in a per-hop manner. Only $L$-link information is needed at each hop, and only $M(L-1)$ comparisons are required to perform the routing. It was shown that ad-hoc routing can also achieve full diversity gain. However, the power gain of ad-hoc routing is determined by the variances of the channel gains of each hop. Hence, for an idealized linear network, 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, in which a joint optimization is performed every $N$ hops. The outage analysis of these three routing strategies was verified through simulations. The analysis of the performance loss and implementation complexity of ad-hoc routing and $N$-hop routing compared to optimal routing was also provided for the proper choice of routing strategies and parameters.

## ACKNOWLEDGEMENT

The authors thank the editor and the anonymous reviewers for their helpful and constructive comments.

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TABLE I

COMPARISONS OF THREE ROUTING STRATEGIES

| Routing Strategy | Number of Comparisons | Required Channel Information |
|---|---|---|
| Optimal | $2(M-2)L^2-(M-4)L-1$ | $Q=(M-2)L^2+2L$ links |
| Ad-hoc | $M(L-1)+1$ | $L$ links in the first $M-2$ hop and $2L$ in $M-1$ hops |
| $N$-hop | $2L^2(M-T-1)+L(2T-M+2)-T$ | $L+(N-1)L^2$ links in the first<br>$T-1$ groups<br>$2L+(N-2)L^2$ in the last group |

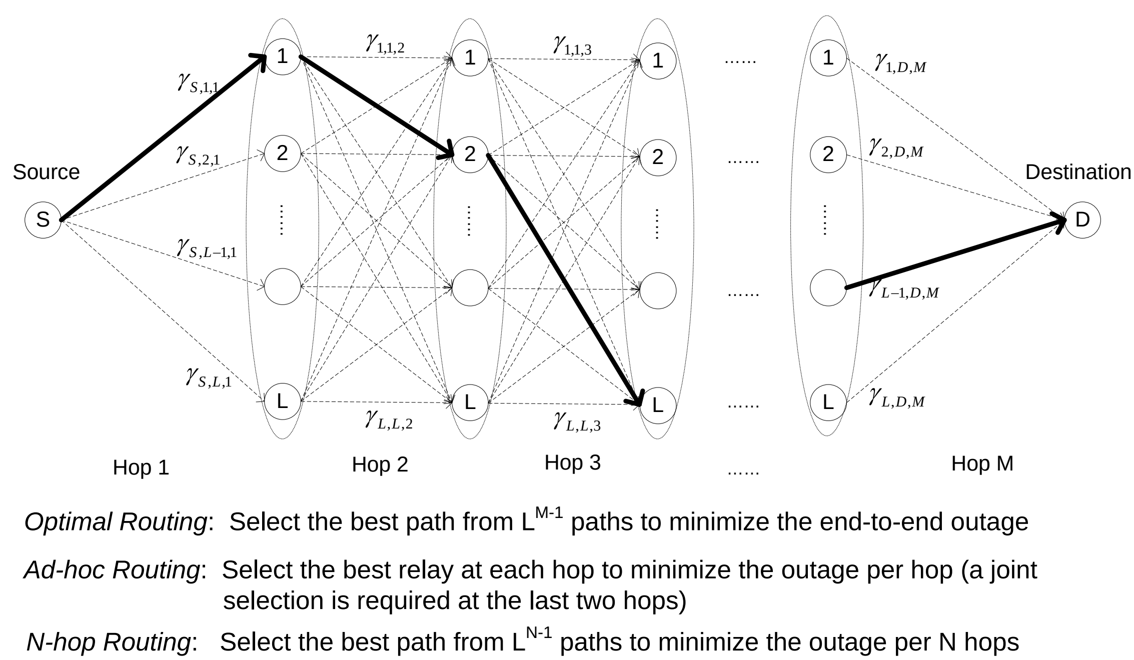


Fig. 1. Linear network model with $M$ hops and $L$ relays in each hop.

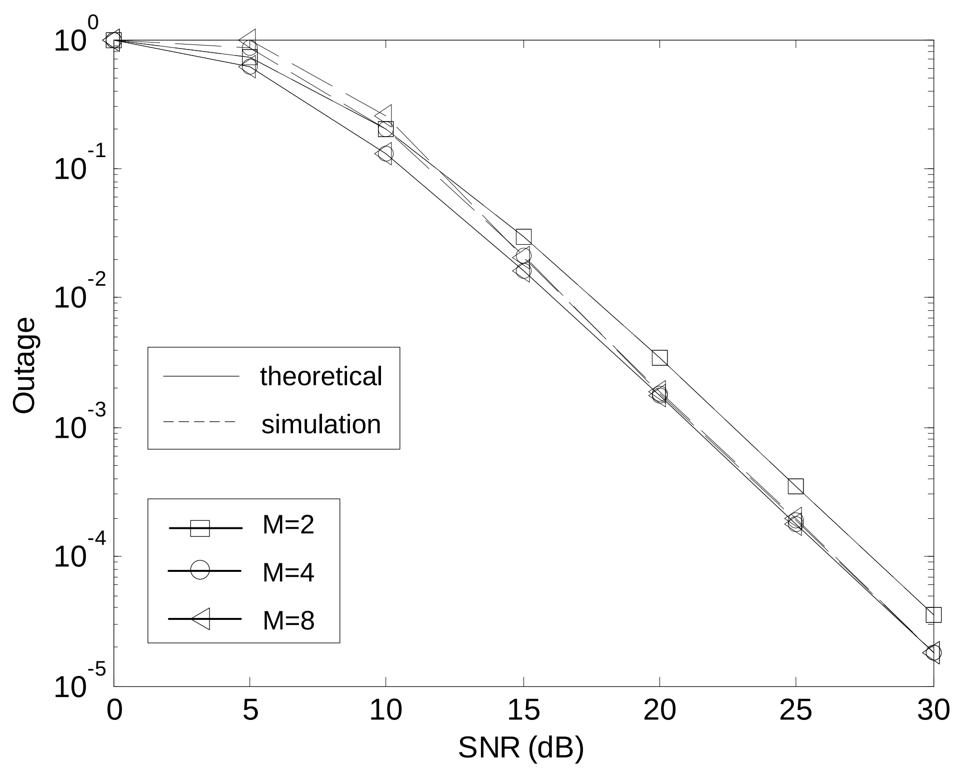


Fig. 2. Outage performance of optimal routing for different numbers of hops, $M$ ($L = 2$).

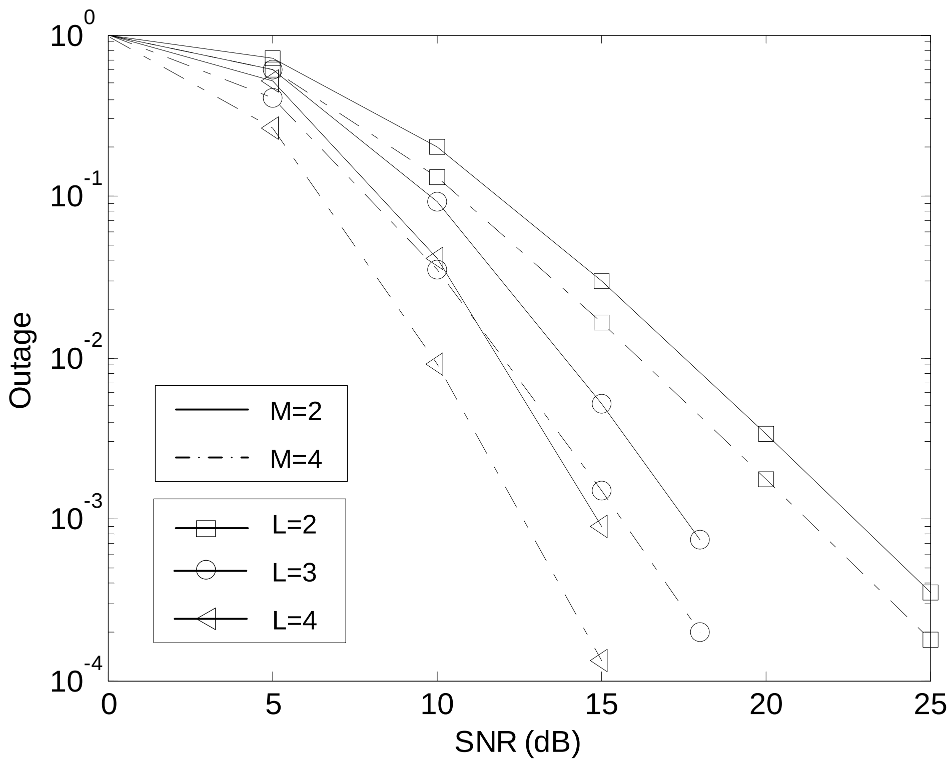


Fig. 3. Outage performance of optimal routing with different numbers of relays, $L$, and $M = 2$ or $4$ hops.

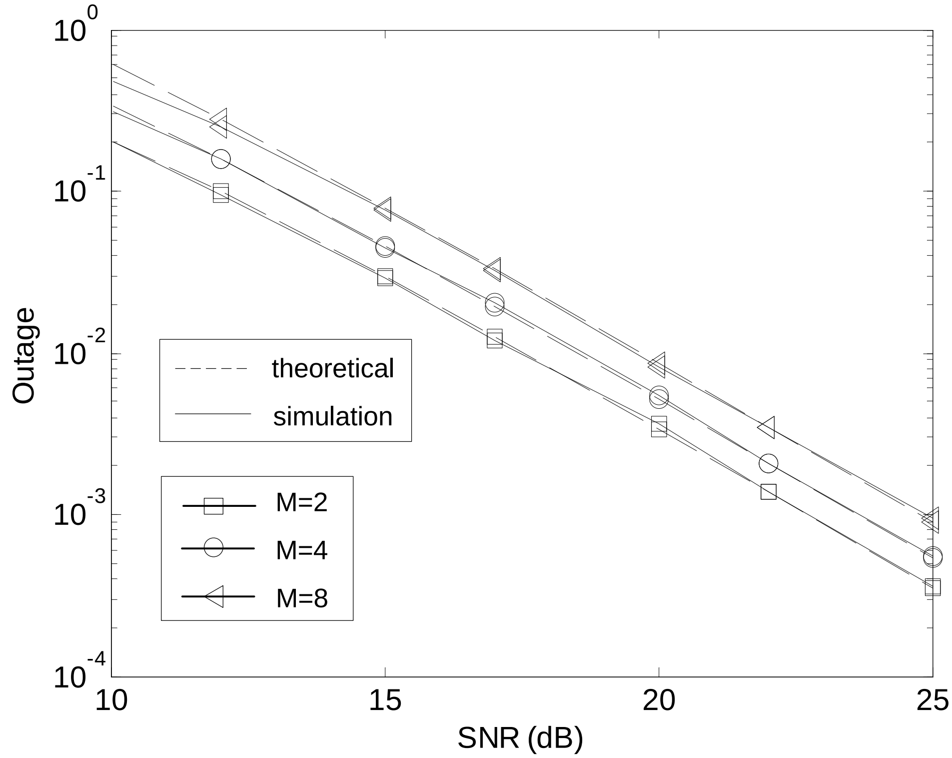


Fig. 4. Outage performance of ad-hoc routing with different numbers of hops, $M$ ($L = 2$).

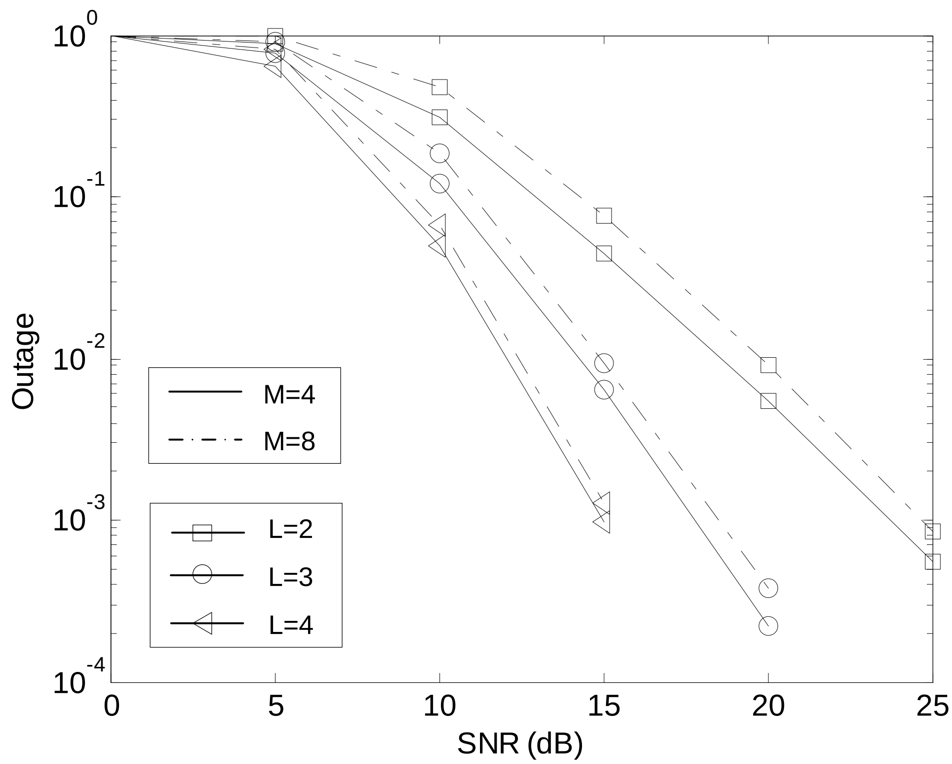


Fig. 5. Outage performance of ad-hoc routing with different numbers of relays, $L$, and $M = 4$ or $8$ hops.

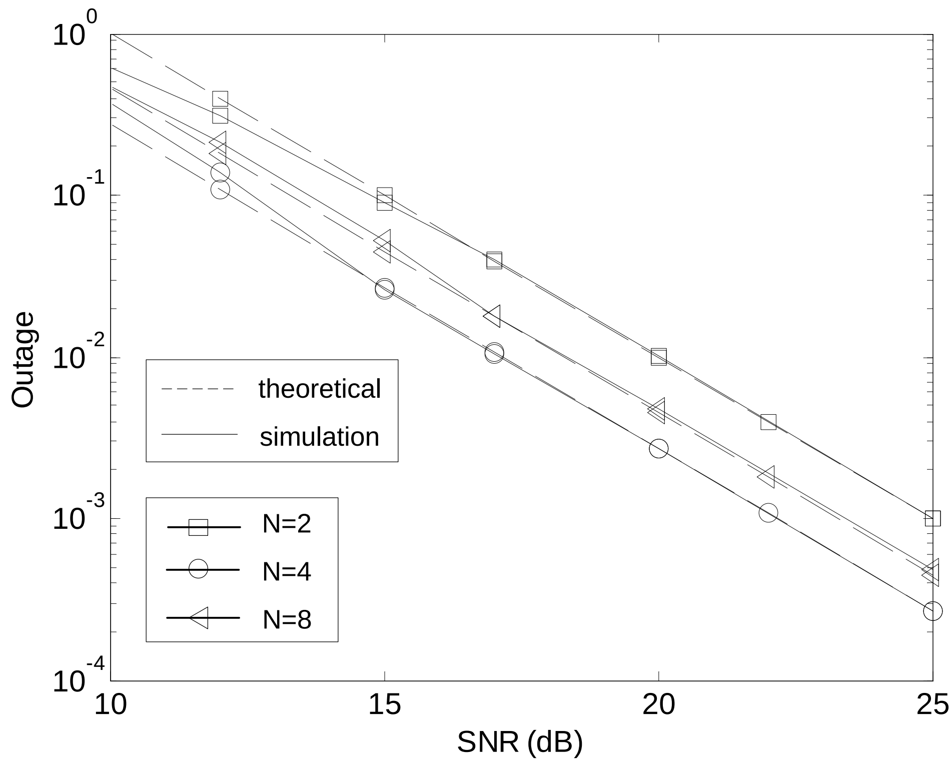


Fig. 6. Outage performance of $N$-hop routing with different values of $N$ when $L = 2$ and $M = 16$.

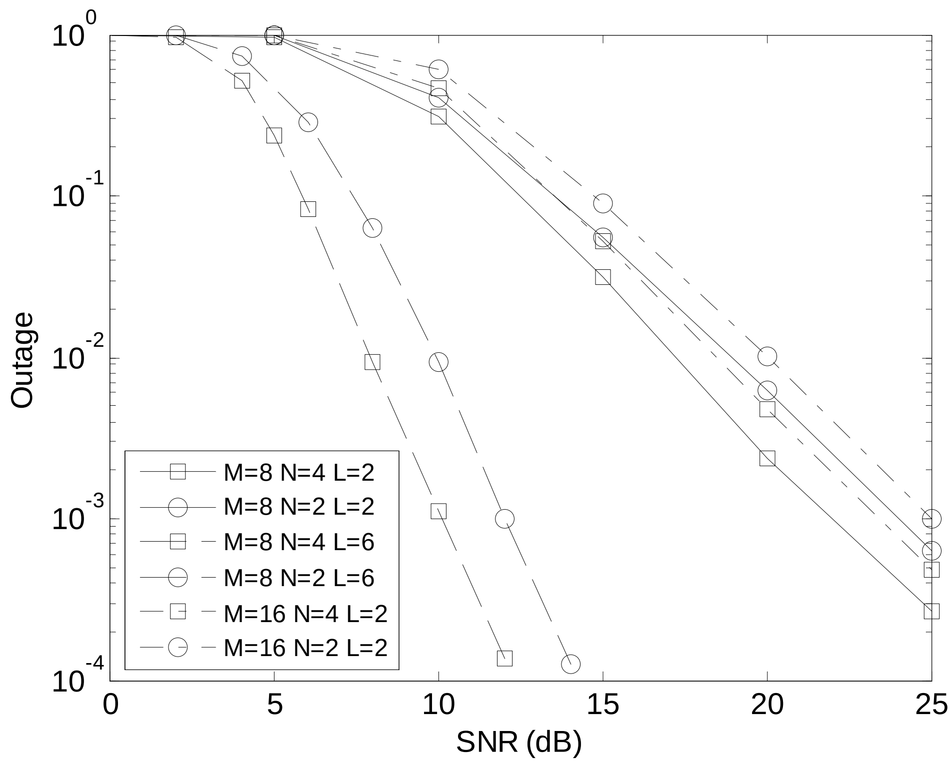


Fig. 7. Outage performance of $N$-hop routing with different values of $L$ and $N$ ($M = 8$ or 16).

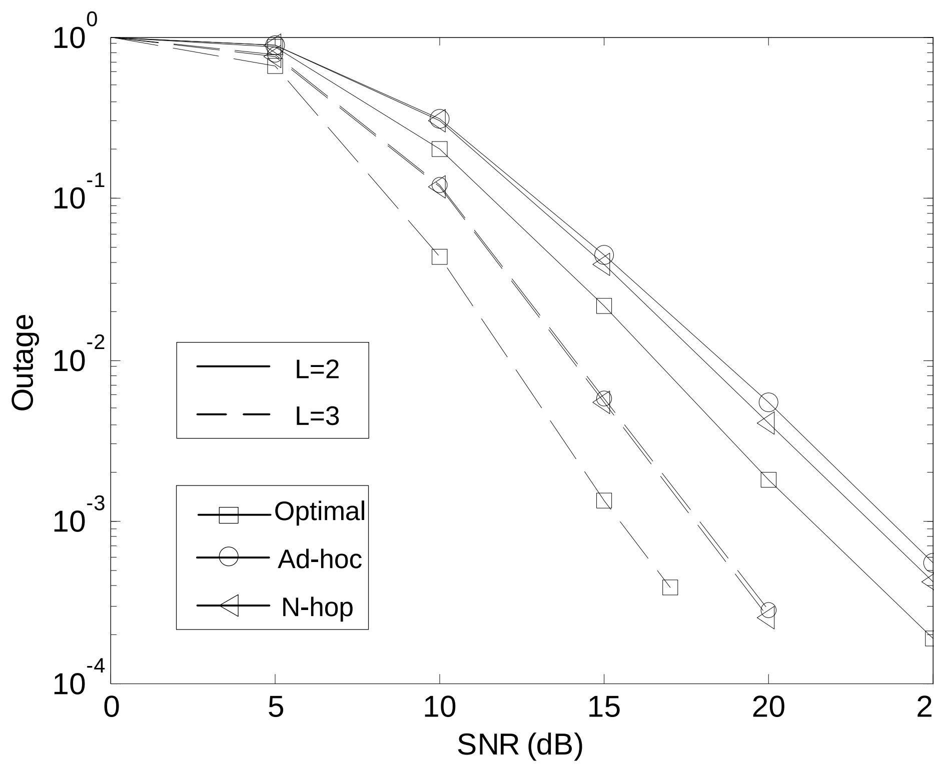


Fig. 8. Outage performance of optimal routing, ad-hoc routing and $N$-hop routing ($N = 2$) with different values of $L$ ($M = 4$) in idealized linear networks.

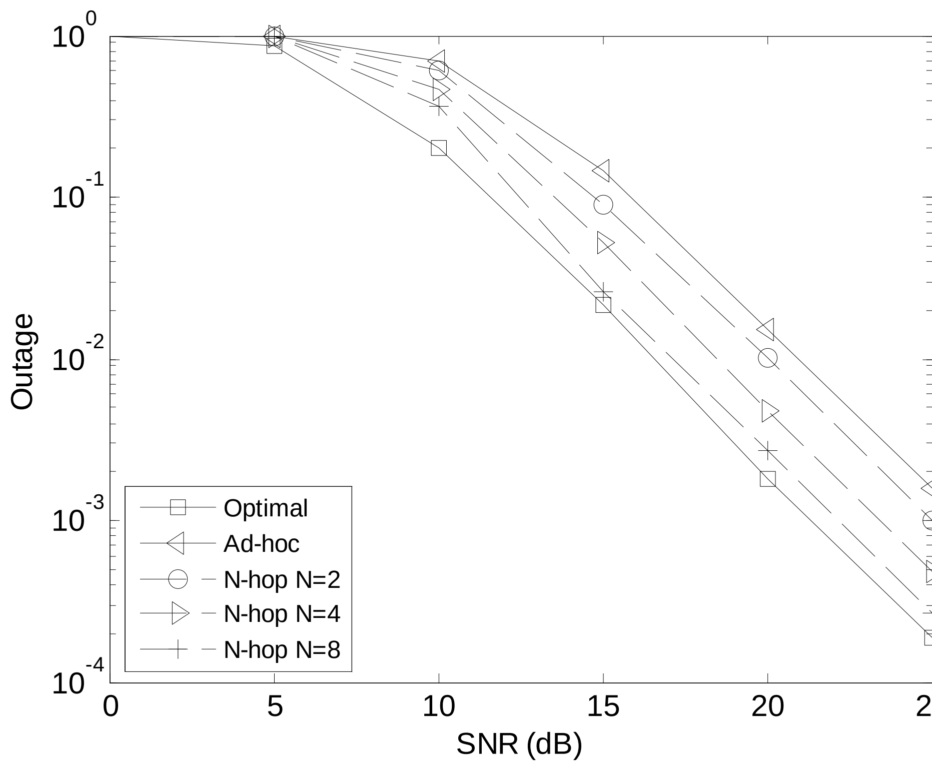


Fig. 9. Outage performance of optimal routing, ad-hoc routing and $N$-hop routing when $M = 16$ and $L = 2$ in idealized linear networks.

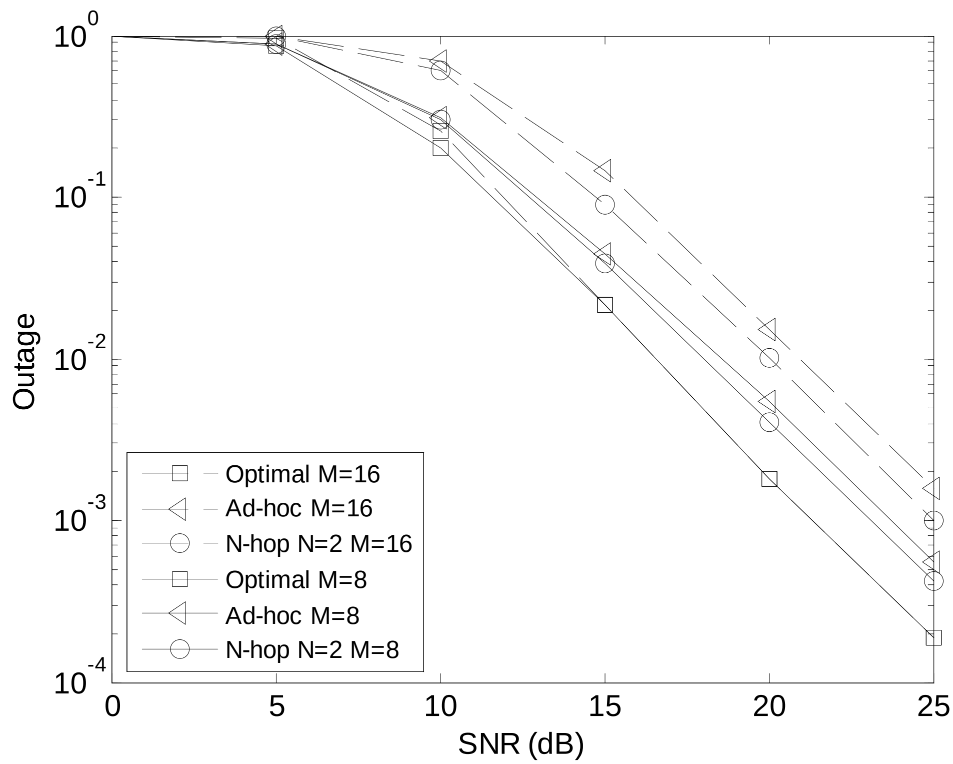


Fig. 10. Outage performance of optimal routing, ad-hoc routing and $N$-hop routing with different numbers of hops, $M$, ($L = 2$) in idealized linear networks.

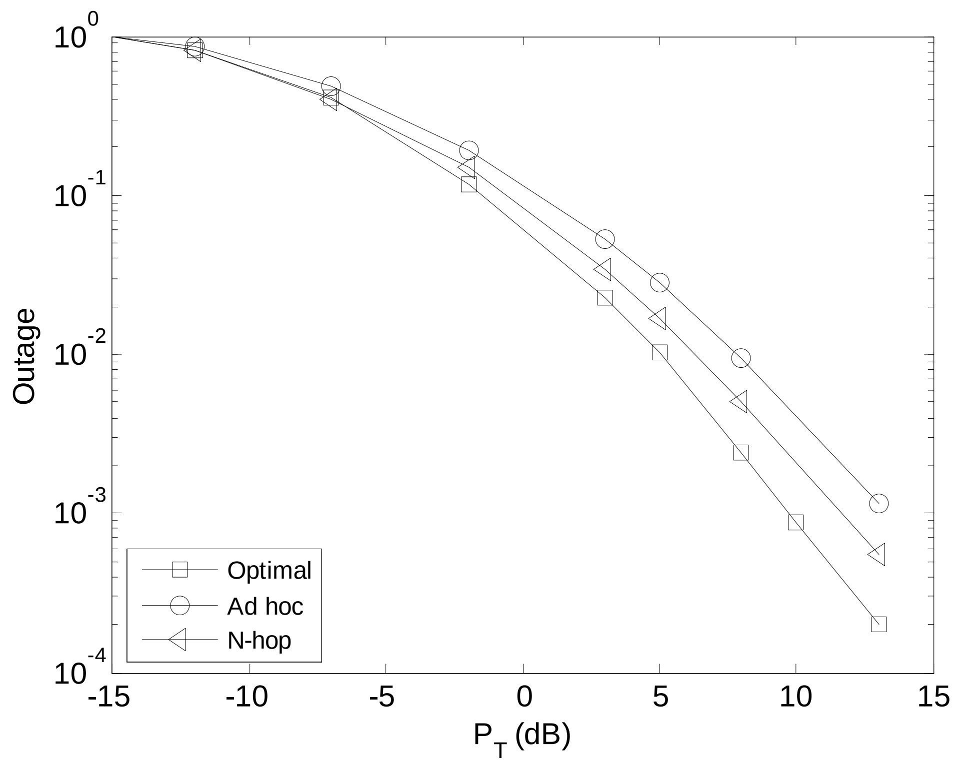


Fig. 11. Outage performance of optimal routing, ad-hoc routing and $N$-hop routing (N=2) in random networks with $M = 8$ ($L = 2$).

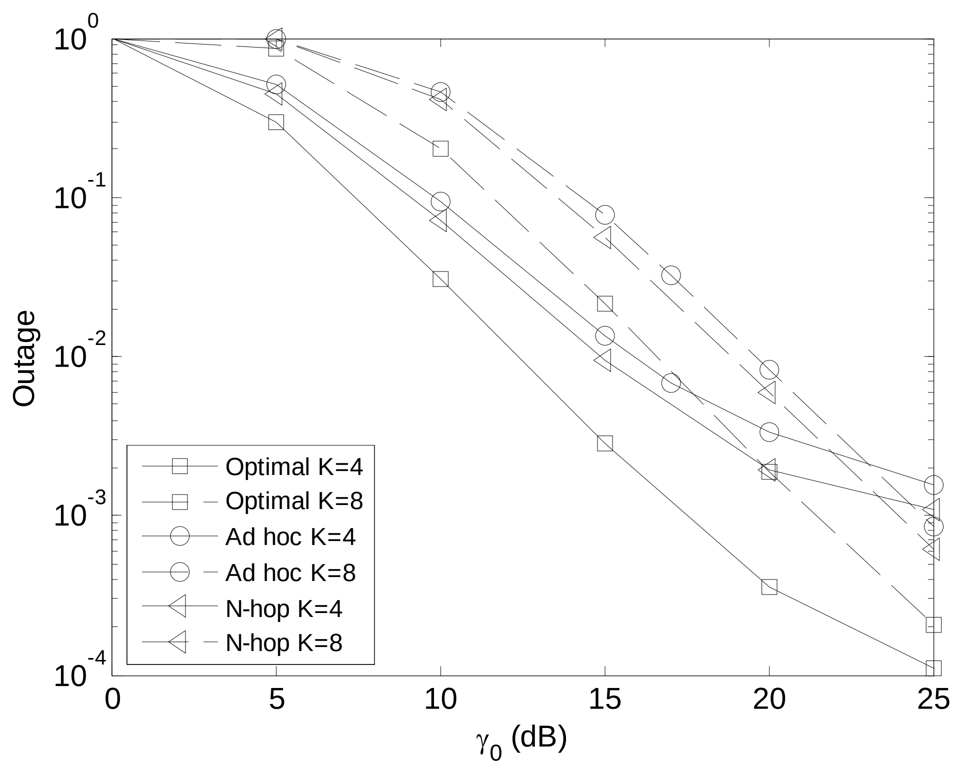


Fig. 12. Outage performance of optimal routing, ad-hoc routing and $N$-hop routing (N=2) with spatial reuse, $M = 8$ and $L = 2$ in idealized linear networks.