On Optimum Relay Deployment in a Multi-Hop Linear Network with Cooperation

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Abstract—There has been a growing interest in designing relay deployment strategies for cooperative wireless networks. In this paper, we focus on multi-hop, cluster-based, linear networks. Several relay selection strategies are applied to achieve the cooperative diversity benefits. We derive the number of hops that minimizes the end-to-end outage probability. On the other hand, if the required overhead for cooperation is considered, increasing the number of relays in each cluster can degrade the performance. Using an information-theoretic approach, we also investigate the number of relays that maximizes the throughput. Simulation results are presented to verify the analysis.

I. INTRODUCTION

Wireless ad hoc networks, such as wireless sensor networks (WSN) and mobile ad hoc networks (MANET), have been extensively studied [1]-[3]. Relaying techniques are commonly applied for accomplishing the transmission in ad hoc networks since, in practical scenarios, the direct link between the source and destination could be very weak due to the possibly severe signal attenuation from path-loss and shadow fading. The relay deployment problem, which aims to optimally position the relays, is a key design issue that helps provide better network performance (network connectivity, lifetime, etc.) [4]-[7].

Cooperative communication has been proposed as a promising approach to combat fading in wireless networks. By exploiting the broadcast nature of the wireless medium, cooperation utilizes distributed relays to help transmit the desired signal to achieve spatial diversity gain. Cooperation in ad hoc networks has been extensively studied. For example, in [7], an approach for applying cooperative techniques and relay deployment to maximize the network lifetime has been proposed. In [8], relay selection strategies have been designed to achieve full diversity gain for a multi-hop linear network with cooperative relays, and outage performance for different schemes has been analyzed.

In ad hoc networks, the multi-hop transmission process can be viewed as a one-dimensional linear network once the route is determined by a given routing protocol [9]. Fig. 1 illustrates a multi-hop ad hoc network, which can be simplified to a linear network model as illustrated in Fig. 2. The linear network
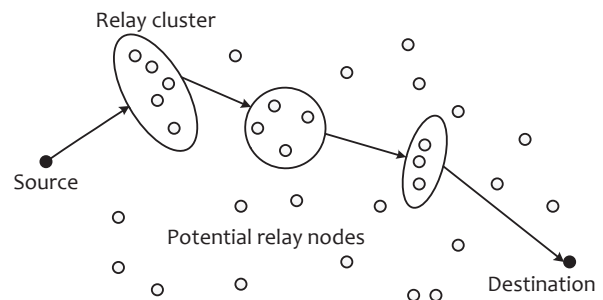
Fig. 1. Multi-hop wireless ad hoc network. The route contains a source-destination pair, and several relay clusters. The nodes in each cluster are selected from the potential relay nodes (small circles) according to a given routing protocol.

model is widely used to provide insights for practical multi-hop network design.

In this paper, we focus on a multi-hop linear network with cooperative relays, which has been investigated in [8]. We strive to answer the following questions: 1) Where should the relay clusters be located? 2) How many relays should be in each cluster? First, according to the outage analysis in [8], we derive the optimum relay cluster locations which minimize the end-to-end outage probability. Further, we consider the required cooperation overhead by using the overhead-performance tradeoff analysis in [10]-[11]. A larger number of relays could lead to worse performance because of the extra overhead costs in implementing cooperation. The optimum number of relays, which maximizes the throughput, is then discussed.

The rest of the paper is organized as follows. Section II presents the system model. Section III analyzes the optimum relay deployment strategy. In Section IV, simulation results are given to verify our analysis. Finally, we conclude in Section V.

II. SYSTEM MODEL

A. Network Topology

We consider a generalized N-hop linear network model. The system under consideration consists of a source node S and a destination node D, and $N-1$ intermediate relay clusters which are located between the source and destination. The number of nodes in the jth relay cluster is denoted as L_j, $j = 1, 2, \cdots, N - 1$; there are $\prod_{j=1}^{N-1} L_j$ distinct end-to-end

paths in the network. Each path can be represented by a set containing the indices of the relays in all the clusters. The source-to-destination distance is assumed to be d_s.

We assume that the inter-cluster distance is much larger than the intra-cluster distance. Since it has been shown in [12] that equally spaced relays are optimum in a linear network, we also assume that the relay clusters are equidistant (i.e., the inter-cluster distance is d_s/N). All nodes in the network are assumed to be half-duplex transceivers which are equipped with only one antenna.
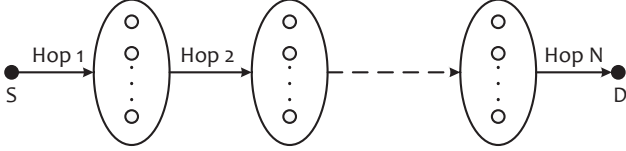

Fig. 2.   Linear network model with cooperative relays.

B. Communication Schemes

We consider a selective decode-and-forward, fixed-rate, relaying strategy (i.e., at each hop, only one relay node is selected to forward the signal at a constant transmission rate). Two selection schemes are investigated in this paper: optimal selection (select the "best" path from all end-to-end paths) and ad hoc selection (select the "best" path at each hop) [8].

For the sake of simplicity, a time division system without spatial reuse is considered in this paper, i.e., there is only one transmission during any particular time period. We assume that all transmissions are identical and are assigned to equal portions of the available time duration. Also, all nodes use a finite transmit power P over a bandwidth B. Hence, if the desired end-to-end spectral efficiency is η (bps/Hz), the required per-hop spectral efficiency is $N\eta$. Perfect time and frequency synchronization among all nodes is assumed.

The channels are assumed to follow a quasi-static flat Rayleigh fading model with path loss. Perfect channel state information (CSI) is always available at the receivers. Suppose that the transmission path (selected by some specific criteria) is represented by $\{r_1, r_2, \cdots, r_{N-1}, r_N\}$, where r_j is the selected relay in the jth cluster, and r_N denotes the destination node. Then, the signal received at r_j can be expressed as

$$y = \sqrt{P \left(\frac{d_s/N}{d_0} \right)^{-\alpha}} h_{r_{j-1}, r_j} x + z, \qquad (1)$$

where x is the signal transmitted by the previous hop, h_{r_{j-1}, r_j} is the channel coefficient between r_{j-1} and r_j, which is modeled as a complex Gaussian random variable with zero mean and variance $1/2$ per complex dimension, and z is additive white Gaussian noise with zero mean and variance $N_0/2$. In (1), α is the path-loss exponent (typically between 2 and 4), d_0 is the reference distance [13]. To simplify our analysis, we will assume $d_0 = 1$ m in this paper. Different values for this parameter will not affect the analysis which

follows. Then, the signal-to-noise ratio (SNR) at r_j is

$$\gamma_j = \frac{P}{N_0 B} \left(\frac{d_s}{N} \right)^{-\alpha} |h_{r_{j-1}, r_j}|^2. \qquad (2)$$

C. Performance

Here, we focus on the end-to-end outage performance. The end-to-end spectral efficiency can be expressed as

$$C = \frac{1}{N} \left[\log \left(1 + \min_{j=1,2,\cdots,N} \gamma_j \right) \right], \qquad (3)$$

and the outage probability is

$$
\begin{aligned}
p_{\text{out}} &= \Pr \left\{ \frac{1}{N} \left[\log \left(1 + \min_{j=1,2,\cdots,N} \gamma_j \right) \right] < \eta \right\} \\
&= \Pr \left\{ \min_{j=1,2,\cdots,N} \gamma_j < 2^{N\eta} - 1 \right\} \\
&= \Pr \left\{ \min_{j=1,2,\cdots,N} |h_{r_{j-1}, r_j}|^2 < \frac{2^{N\eta} - 1}{N^\alpha \gamma_d} \right\} \\
&= \Pr \left\{ g_{\min} < \frac{2^{N\eta} - 1}{N^\alpha \gamma_d} \right\},
\end{aligned}
\qquad (4)
$$

where $\gamma_d = \frac{P}{N_0 B} d_s^{-\alpha}$ is the received SNR for the direct link, and $g_{\min} = \min |h_{r_{j-1}, r_j}|^2$ is the channel gain for the worst hop in the selected transmission path. Obviously, the end-to-end outage is determined by the bottleneck hop.

We notice that the channel gains $|h_{r_{j-1}, r_j}|^2$, $j = 1, 2, \cdots, N$ are identically distributed exponential random variables, but they are not independent; the channel at the jth hop depends on which nodes are selected in the previous relay clusters.

III. OPTIMUM RELAY DEPLOYMENT STRATEGY

In this section, we answer the two questions posed in Section I. First, we discuss the optimum number of hops for a multi-hop linear network with cooperative relays, and then determine the best relay placement. To simplify the analysis, we first assume that $L_1 = L_2 = \cdots = L_{N-1} = L$. However, we also extend our analysis to more practical scenarios (for example, L_j is a random variable and not necessarily equal for all j). Then, we investigate the optimum number of relays per cluster, which can balance the system performance and the required overhead.

A. Optimum Number of Hops (Optimal Selection)

For the optimal relay selection strategy, the path which maximizes the channel gain for the bottleneck link, $g_{\min}$, will be chosen. Although there are $\prod_{j=1}^{N-1} L_j = L^{N-1}$ distinct end-to-end paths, some of these paths might share the same bottleneck link. Let Ψ denote the set that contains the bottleneck links of all possible paths, and ψ is the number of distinct elements in Ψ. In other words, ψ represents the degrees of freedom that can be utilized for diversity gain.

It has been shown in [8] that the end-to-end outage probability for optimal selection can be upper bounded by

$$p_{\text{out}} < \left(1 - \exp \left(-\frac{(2^{N\eta} - 1)}{N^\alpha \gamma_d} \right) \right)^\psi, \qquad (5)$$

According to Lemma 1 in [8], $\psi \geq L$. So

$$p_{\text{out}} < \left(1 - \exp\left(-\frac{(2^{N\eta} - 1)}{N^{\alpha}\gamma_d}\right)\right)^{L} = p_{\text{out}}^{*}. \quad (6)$$

It is easy to show that the optimum $N^{\star}$ that minimizes the upper bound p_{out}^{*} satisfies

$$\alpha + N^{\star}\eta 2^{N^{\star}\eta}\ln 2 - \alpha 2^{N^{\star}\eta} = 0. \quad (7)$$

Using techniques similar to those in [14], we have

$$N^{\star} = \arg\min p_{\text{out}}^{*} = \left[\frac{1}{\eta\ln 2}\left(\alpha + \mathcal{W}(-\alpha e^{-\alpha})\right)\right]_{+}, \quad (8)$$

where $[\cdot]_{+}$ is the operator which rounds the operand to the nearest positive integer, and $\mathcal{W}(\cdot)$ is the principal branch of the Lambert W function [15].

In [8], an approximation for p_{out} is provided as

$$p_{\text{out}} \approx 2\left(1 - \exp\left(-\frac{(2^{N\eta} - 1)}{N^{\alpha}\gamma_d}\right)\right)^{L}$$
$$- \left(1 - \exp\left(-\frac{(2^{N\eta} - 1)}{N^{\alpha}\gamma_d}\right)\right)^{2L}, \quad (9)$$
$$+ o\left(\left(-\frac{(2^{N\eta} - 1)}{N^{\alpha}\gamma_d}\right)^{L}\right)$$

where the last term is negligible in the high-SNR regime. We can prove that the number of hops $N^{\star}$ in (8) minimizes the approximation as well. On the other hand, for a fixed-rate scheme, the end-to-end throughput can be defined as $\eta(1 - p_{\text{out}})$. Therefore, $N^{\star}$ in (8) also maximizes the throughput.

Remark 1: Eq. (8) is exactly the same as the closed-form expression for the optimum number of hops for a linear network in an AWGN channel [9]. In [9], the power consumption that guarantees a given transmission rate is minimized. Note that there is an inherent power constraint in our model; our problem, which maximizes the rate by using a specific power, can be stated as a dual problem of the optimization problem in [9]. The duality gap is zero since both problems are convex and linearity constraint qualification conditions [16] are satisfied. This also explains why the optimum number of hops only depends on the rate and the path-loss exponent.

Remark 2: According to (8), the optimum number of hops does not depend on the number of relays in each cluster, i.e., *diversity does not affect the optimum number of hops when the relay clusters are equidistant.* Obviously, the end-to-end outage performance can be significantly improved when we have diversity gain, however, the number of hops minimizing the outage probability remains the same. The intuitive explanation is that, after we select the path through all relay clusters, we form another linear network which only has one relay per hop. The diversity benefit helps increase the received SNR per hop, however, the structure of the linear network and the derivation of the optimum number of hops do not change.

Remark 3: Eq. (8) can be rewritten as

$$N\eta = \frac{1}{\ln 2}\left(\alpha + \mathcal{W}(-\alpha e^{-\alpha})\right). \quad (10)$$

The right hand side (RHS) of (10) is a constant which only depends on the path-loss exponent α. For example, when $\alpha = 4$, we have $N\eta \approx 5.66$. In [17], the rate which maximizes the transport capacity is also given by the RHS of (10). The result in [17] can be considered as a special case of the work considered here: for single-hop transmission ($N = 1$) with a power constraint, maximizing the transport capacity is equivalent to minimizing the outage.

Note that these results only hold for a fixed-rate relaying scheme. If rate-adaptive techniques are also taken into account or the ergodic capacity is chosen as the performance measure, the optimum number of hops will be different; this is a topic we are currently investigating.

If we assume the L_j's are not necessarily all equal, the upper bound in (5) can still be used. The following lemma helps to determine the optimum number of hops in this scenario.

Lemma 1. Ψ *includes at least* $\min\{L_1, L_2, \cdots, L_{N-1}\}$ *distinct links, i.e.,* $\psi \geq L_{\min} = \min\{L_1, L_2, \cdots, L_{N-1}\}$.

Proof: Without loss of generality, we assume that $L_1 = L_{\min}$. In this case, a link in the first hop can be shared by at most $\prod_{j=2}^{N-1} L_j$ paths, which implies that at least L_1 links are required to cover all possible paths, that is, $\psi \geq L_{\min}$. ∎

According to Lemma 1, we can rewrite (5) as

$$p_{\text{out}} < \left(1 - \exp\left(-\frac{(2^{N\eta} - 1)}{N^{\alpha}\gamma_d}\right)\right)^{L_{\min}} = p_{\text{out}}^{**}. \quad (11)$$

Obviously, $N^{\star}$ in (8) can also minimize p_{out}^{**}.

In a practical wireless ad hoc network, the number of relays in each cluster should be a random variable. We can assume that all the nodes in an ad hoc network form an m-dimension homogenous Poisson point process of intensity λ in $\mathbb{R}^m$ [18]. Then the probability of finding ℓ nodes in a bounded space A is given by a discrete Poisson distribution

$$A(\ell) = \Pr\{\ell \text{ nodes in A}\} = e^{-\lambda\phi(A)}\frac{(\lambda\phi(A))^{\ell}}{\ell!}, \quad (12)$$

where $\phi(A)$ is a standard Lebesgue measure (area, volume, etc.) of A. We can state that $\mathcal{L} = \lambda\phi(A)$ is the average number of decoded nodes in the given relay cluster A. Therefore, we assume that $L_1, L_2, \cdots, L_{N-1}$ are i.i.d. Poisson random variables with parameter $\mathcal{L}$, and

$$\Pr\{L_{\min} = \ell\} = \left(1 - \frac{\Gamma(\ell, \mathcal{L})}{\Gamma(\ell)}\right)^{N-1}$$
$$- \left(1 - \frac{\Gamma(\ell+1, \mathcal{L})}{\Gamma(\ell+1)}\right)^{N-1}, \quad (13)$$

where

$$\Gamma(\ell, \mathcal{L}) = \int_{\mathcal{L}}^{\infty} t^{\ell-1}e^{-t}\,dt \quad (14)$$

is the incomplete gamma function.

Combining (11) and (13), we can obtain an upper bound on the average outage probability with a random number of potential relays

$$p_{\text{out}} < \sum_{\ell=0}^{\infty} \Pr\{L_{\min} = \ell\}\left(1 - \exp\left(-\frac{(2^{N\eta} - 1)}{N^{\alpha}\gamma_d}\right)\right)^{\ell}, \quad (15)$$

and show that $N^\star$ in (8) also minimizes the upper bound in (15). The proof is similar and is omitted here.

Since the diversity does not affect the optimum number of hops even if we consider the randomness of the decoded sets, we can easily extend the results for linear networks with a single relay per hop [9][12][14][17] to our scenarios. In the following, we assume $L_1 = L_2 = \cdots = L_{N-1} = L$.

B. Optimum Number of Hops (Ad hoc Selection)

In an ad hoc selection scheme, the relay selection is performed in a per-hop manner and performance is suboptimal. A high-SNR approximation is provided in [8]

$$p_{\text{out}} \approx (N - 2 + 2^L)\left(\frac{2^{N\eta} - 1}{N^\alpha \gamma_d}\right)^L, \tag{16}$$

We can show that the optimum N must satisfy

$$N(\ln N)^2 + (\beta + \zeta)N \ln N + \zeta \ln N - \alpha\beta N + \alpha\beta = 0, \tag{17}$$

where $\beta = (2^L - 2)\eta \ln 2$, $\zeta = \alpha - \frac{1}{L}$. A closed-form expression for the optimum N cannot be obtained since (17) is a nonlinear transcendental equation; we can solve it by numerical methods. In Section IV, we will show that the optimum number of hops from (17) is very close to the value that satisfies (8).

Suppose we have a source-destination pair with desired spectral efficiency η. Then, we can easily obtain the optimum $N^\star$ based on (8) and then equally place $N^\star - 1$ relay clusters between the source and the destination. Note that $N^\star$ does not depend on the number of relays L, which indicates that we can separate the relay deployment problem into two parts: (1) deciding the locations of the relay clusters and (2) determining the number of relays in each cluster. In the next subsection, we will investigate the optimum number of relays which achieves the best overhead-performance tradeoff.

C. Optimum Number of Relays

Obviously, the outage probability decreases as the number of relays L increases because we have more diversity gain. The outage capacity, $\max_\eta \eta(1 - p_{\text{out}}(\eta))$ (bps/Hz), is thus a monotonically increasing function of L. However, in a realistic system, the receivers require knowledge of the CSI so that the signal can be successfully decoded. This can be facilitated by sending training symbols. Also, the receivers need to feedback some information, such as the CSI or the index of the best path, to implement the relay selection strategies. Intuitively, when we have more relays, we will incur more overhead for the training and selection tasks. The training and feedback overhead, which is also a monotonically increasing function of L, should also be considered. In that case, more relays does not necessarily lead to better performance.

According to [10], the smallest number of training symbols for a multiple-antenna system is equal to the number of transmit antennas. This result can be directly applied to our scenarios. For the optimal selection scheme, we have $L^2(N - 2) + 2L$ links in the network, which requires at least $L^2(N - 2) + 2L$ training symbols to guarantee meaningful

channel estimation. For the ad hoc selection scheme, we need at least L training symbols per hop, and the overall number of training symbols is NL.

The feedback overhead for relay selection has been studied in [11]. In general, $\log L$ feedback bits are required to implement perfect selection among L possible links. Intuitively, $\log L$ is the entropy (uncertainty) of the index for the best link from all L links. For the ad hoc selection scheme, we require $(N - 1)\log L$ feedback bits to choose the path. The analysis for the optimal selection scheme is more complicated. In [11], the overhead-performance tradeoff is only investigated for the single-hop case. We use a simplified analysis to approximate the feedback overhead bits for the optimal selection scheme: since we have to select the best path from all L^{N-1} paths, we have to use at least $\log L^{N-1} = (N - 1)\log L$ bits to denote the index of the selected path. Intuitively, more feedback bits might be required for the optimal selection scheme; however, we use the lower bound here to provide insights about the overhead-performance tradeoff. The analytical study of required feedback bits is the topic of future work.

We note that the optimal and ad hoc selection schemes require the same amount of feedback overhead. However, optimal selection costs much more in training overhead than the ad hoc selection scheme. Note also that the analysis here only provides lower bounds for the required overhead.

Suppose that the feedback signals for updating the selected path are sent periodically with period T (which is usually chosen as 10% of the channel coherence time), and the training symbol duration is $T_s = T/M$, i.e., there are M symbols per block. Then, the spectral efficiency for optimal selection is

$$\eta_{\text{se,opt}} = \left(1 - \frac{L^2(N - 2) + 2L}{M}\right)\eta_{\text{out}}$$
$$- \frac{(N - 1)\log L}{BT} \text{ bps/Hz}, \tag{18}$$

and the spectral efficiency for ad hoc selection is

$$\eta_{\text{se,ad hoc}} = \left(1 - \frac{NL}{M}\right)\eta_{\text{out}}$$
$$- \frac{(N - 1)\log L}{BT} \text{ bps/Hz}, \tag{19}$$

where $\eta_{\text{out}} = \max_\eta \eta(1 - p_{\text{out}}(\eta))$ is the outage capacity. The optimal L which maximizes the spectral efficiency can be obtained numerically. This will be presented in Section IV.

IV. SIMULATION RESULTS

Assume we have a source-destination pair at a distance $d_s = 1$ km. The objective is to place several relays between the source and destination, such that the end-to-end outage performance is optimized. All nodes in the network, including the source and the destination, are supplied with transmit power $P = 20$ dBm over the frequency bandwidth $B = 10$ MHz. The path-loss exponent α is assumed to be 4, and the noise spectral density $N_0 = -174$ dBm/Hz. When no relay is employed, the average received SNR at the destination is

$$\gamma_d = \frac{P}{N_0 B}d_s^{-\alpha} = 4 \text{ dB}. \tag{20}$$

The general conclusions, which can be observed from the following simulation results, do not depend upon the specific values of these parameters.

A. Where Should The Relay Clusters Be Located?

Since equidistant relay clusters have been shown to be optimal, once we know the number of hops which can minimize the outage probability, the optimal relay deployment strategy can be determined. In Figs. 3 and 4, the outage probability is plotted as a function of the number of hops for the optimal and ad hoc selection schemes. The desired spectral efficiency η is assumed to be 2 bps/Hz. As expected, we can observe from Fig. 3 that the optimum number of hops $N^\star$ does not depend on the number of relays L for the optimal selection scheme. The simulation results also verify our analytical results (8). According to Fig. 4, the optimum number of hops for ad hoc selection is almost the same as that given by (8). This indicates that we can use the analysis for the optimal selection scheme to obtain approximate results for the ad hoc selection scheme.
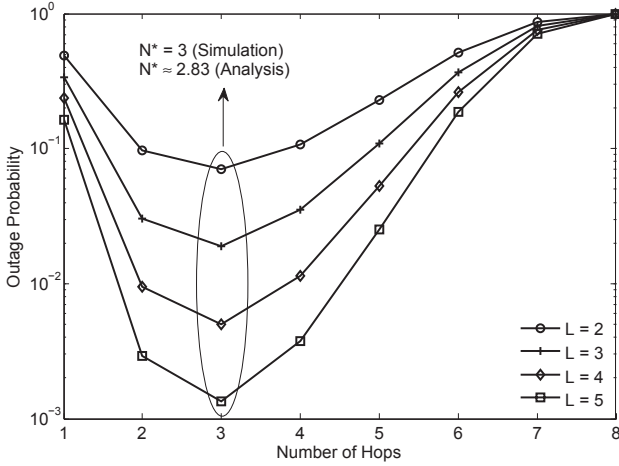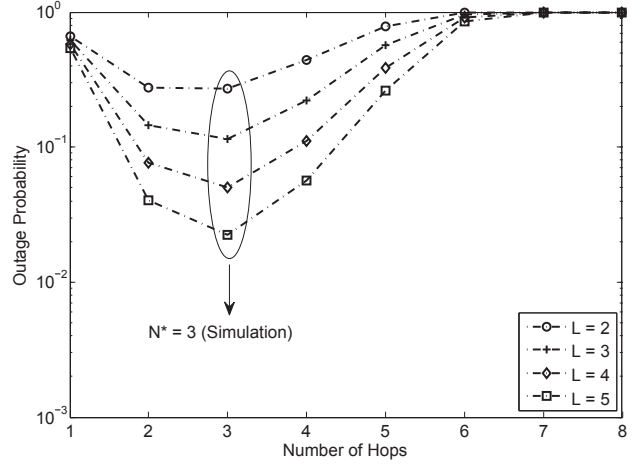

Fig. 4. Optimum number of hops for different values of L (ad hoc selection), $\eta = 2$ bps/Hz, $\gamma_d = 4$ dB.

Fig. 3. Optimum number of hops for different values of L (optimal selection), $\eta = 2$ bps/Hz, $\gamma_d = 4$ dB.

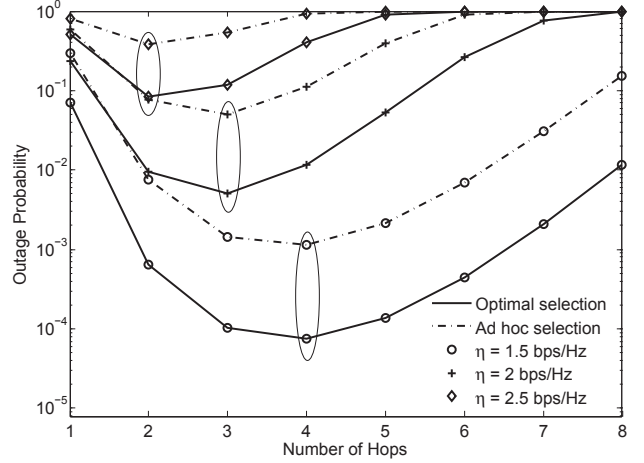Fig. 5. Optimum number of hops for different η (optimal and ad hoc selection schemes). $L = 4$, $\alpha = 4$, $\gamma_d = 4$ dB.

Fig. 5 provides results for different values of the desired spectral efficiency η. The number of relays L is chosen to be 4 in Fig. 5. By rounding the analytical result to the nearest positive integer, we can easily obtain the optimum number of hops and determine where to place the relay clusters. For example, if η is 1.5 bps/Hz, the optimum number of hops is 4 and the optimum per-hop distance is 250 meters.

B. How Many Relays Should Be In Each Cluster?

Now we determine the optimum number of relays by investigating the required training and feedback overhead. Consider a wireless system with moderate mobility such that the coherence time is 10 $m$sec [19]. The feedback signals for updating the selected path are sent every 1 $m$sec. The training symbol duration is assumed to be $T_s = 1$ μsec, i.e., there are 1000 symbols to be transmitted in each block. Intuitively, the impact of overhead becomes negligible with large coherence time and small training duration. The simulation results also verify this intuition; however, here we only present the results for specific parameters to show the importance of overhead.

Figs. 6 and 7 illustrate the tradeoff between the throughput (bps/Hz) and the number of relays per cluster for the optimal and ad hoc selection schemes. One observation is that when the amount of overhead is small, we can always obtain a gain by adding more relays. However, the diversity gain is eventually canceled by the excessive amount of overhead when the number of relays increases. In Fig. 6, the required overhead occupies all the transmission resources when N and L are large, and no meaningful data can be transmitted through the multi-hop network. Another observation is that, although ad hoc selection is sub-optimal in outage, sometimes it provides higher throughput than optimal selection which requires a significant amount of overhead.
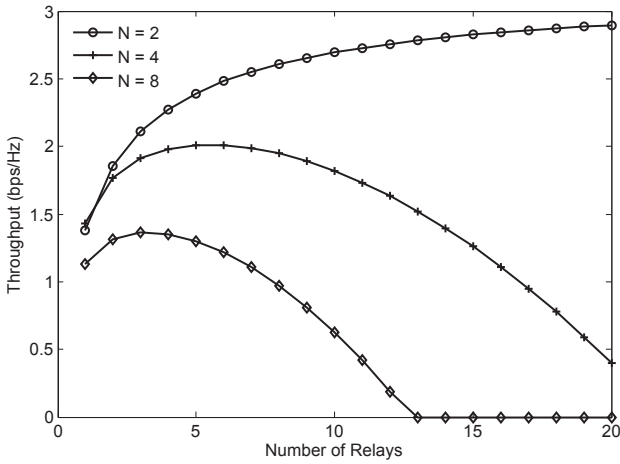
Fig. 6. Optimum number of relays for different values of N (optimal selection), $\gamma_d = 4$ dB.
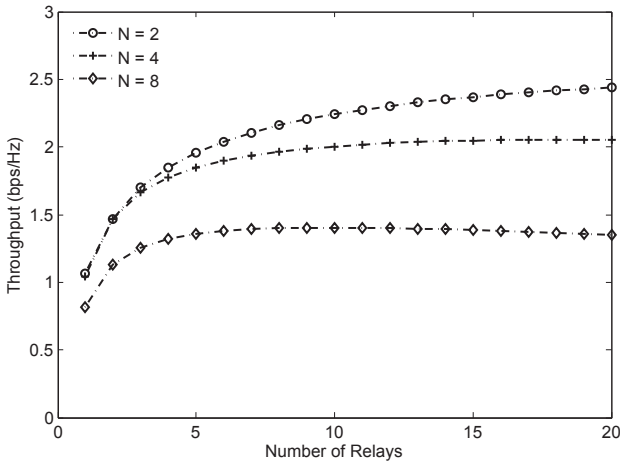

Fig. 7. Optimum number of relays for different values of N (ad hoc selection), $\gamma_d = 4$ dB.

V. CONCLUSION

In this paper, we investigated the optimal relay deployment strategy for a multi-hop linear network with cooperative relays. Two different techniques were considered: optimal selection and ad hoc selection. First, we derived a closed-form expression for the number of hops that minimizes the end-to-end outage probability. We proved that the diversity gain does not affect the optimum number of hops, which means that most existing results for a linear network can also be applied to our scenarios. We also provided lower bounds on the required training and selection overhead for cooperation, and then determined the number of relays that maximizes the throughput. Simulation results were provided to verify the analysis.

In the future, we will quantify the required overhead more precisely so that the optimum number of relays can be better estimated. Instead of assuming a perfect selection process, we will also study the optimal deployment strategy with imperfect relay selection. In addition, we will consider other cooperative techniques such as space time coding and beamforming. Practical network models which consider random distributed nodes and intra-cluster distance will also be investigated.

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