Routing Strategies in Broadband Multihop Cooperative Networks

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***Abstract*— Two fundamental properties of wireless networks, the variable link quality and the broadcast nature of the transmission, have often been ignored in the design of routing protocols. In this paper, we address the routing issue in broadband systems from a link-layer point of view. We focus on a clustered multihop wireless network. A link quality metric is first proposed to measure broadband links; then, three routing strategies, which were proposed in [1] for flat fading scenarios, are re-designed to achieve cooperative and frequency diversity gain. The outage analysis and simulation results of the proposed three routing strategies show that all three protocols can achieve $L(d_c+1)$-order diversity, where L is the number of relays in each relay cluster and d_c is the error correcting capability of the linear block code. The outage of optimal routing remains constant with an increase in the number of hops, M. While, the outage of ad-hoc routing increase linearly. N-hop routing, where a joint optimization is performed every N hops, can achieve a good complexity-performance tradeoff.**

***Index Terms*— Routing, cooperative networks, multihop, OFDM**

I. INTRODUCTION

Multihop wireless networks have attracted much attention in the last few years, and many routing protocols have been proposed, such as Dynamic Source Routing (DSR) [2], Ad hoc On Demand Distance Vector (AODV) [3] and Destination-Sequenced Distance Vector (DSDV) [4]. 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. Most of these routing protocols were also developed based on point-to-point error-free links aiming at the shortest path or the minimum number of hops (for example, see [5-7]). Thereby, two fundamental properties of wireless networks have often been ignored: the variable quality of wireless channels and the broadcast nature of wireless transmissions. As pointed out in [8-10], the stochastic nature of the fading channel and the fact that the signal-to-noise ratio (SNR) is a random variable should not be neglected. Also, minimum-hop routing might lead to a path that uses longer range links of marginal quality [11-12]. So, the routing protocols developed for wired networks will perform suboptimally in wireless networks.

To exploit the broadcast nature of wireless transmission, the cooperative transmission has been proposed (for example, see [13-16]). In these systems, a group of single-antenna nodes transmit together as a "virtual antenna array," obtaining diversity gain, as well as other advantages, without requiring multiple antennas at individual nodes.

Three routing strategies have been proposed in [1] for flat fading channels to fully exploit the diversity gain provided by the cooperation among relays: (1) Optimal routing, in which channel state information for all the links and a joint optimization are required, has the best performance. (2) Ad-hoc routing, in which relay selection is performed in a per-hop manner so that only L-link information is needed at each hop, is a good choice for multihop networks with small number of hops. (3) N-hop routing, in which a joint optimization is performed every N hops, provides a flexible complexity-performance tradeoff.

In this paper, we extend these three routing protocols to broadband systems. Orthogonal Frequency Division Multiplexing (OFDM), which is the underlying physical-layer technology for IEEE802.11 (WiFi) [17], as well as for digital audio [18] and video broadcasting [19], is adopted to enable the broadband high bit rate transmission. To exploit the frequency diversity, an error correcting code is employed across subchannels (as is normally used in OFDM systems). Routing strategies are designed to exploit the diversity in frequency and through cooperation. To measure the coded link quality, a link quality metric is first proposed. Then, the three routing protocols are re-designed according to the proposed link quality metric.

The outage analysis and simulation results of the proposed three routing strategies will show that each scheme can achieve $L(d_c+1)$-fold diversity order, where L is the number of relays in a relay cluster and d_c is the error correcting capability of the linear block code. 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, while, both ad-hoc and N-hop routing suffer a linear increase in outage. The outage behavior of these three routing strategies is similar to their outage behavior in a flat fading scenario [1]. In the broadband scenario, however,

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one additional dimension (frequency) is exploited and a higher diversity order, $L(d_c+1)$, is achieved, compared to the L-fold diversity order achieved in flat fading scenarios.

The paper is organized as follows. The system model is described in Section II. In Section III, we propose a link quality metric for coded OFDM systems, and three routing strategies and outage analysis are presented in Section IV. Simulation results are given in Section V. Finally, Section VI summarizes and concludes the paper.

II. SYSTEM MODEL

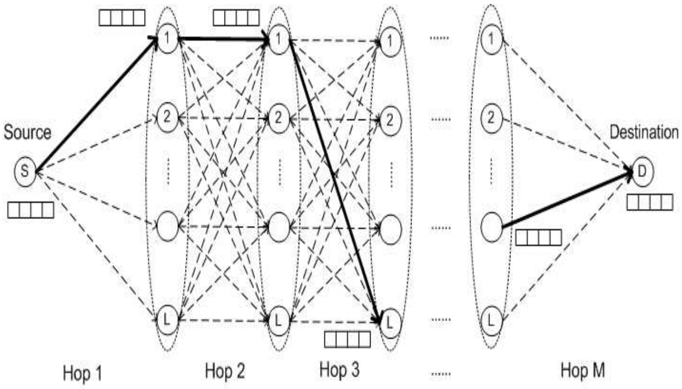
We consider an idealized clustered M-hop linear network model with L relays in each cluster as shown in Fig. 1. $M-1$ relay clusters are equally spaced between the source node and the destination node. The nodes in a specified relay cluster are close together and cooperate in signal transmission and reception. 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. We consider a network with only one path active for each source-destination pair and thus there is no interference between nodes. under these conditions, equally spaced relay clusters are the best in terms of outage performance. The same linear model has been widely used (see [20]-[23]). An OFDM transceiver with Q subchannels is employed in each node to combat frequency-selective fading. We assume that a (Q,U) linear block code with symbol error-correcting capability d_c is adopted in the transmission to exploit the frequency diversity. We also assume that only one source transmits during each particular period.

A *selective* decode-and-forward relaying strategy is used. 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 following relay cluster. Although exploiting all the signals transmitted by multiple previous nodes can greatly improve the energy-efficiency [21]-[23], we assume that a certain receiving node only uses the signal transmitted by its neighboring relay cluster. This approach allows us to concentrate on the design and comparisons of routing strategies and the results developed here can be easily combined with the techniques in [21]-[23].

We assume perfect time and frequency synchronization among nodes and the inclusion of a cyclic prefix that is long enough to accommodate the delay spread of the channel. With these assumptions, the received signal in the qth subchannel of relay node i from relay node j at hop m is

$$R_{i,j,m}(q) = X_{i,j,m}(q)H_{i,j,m}(q) + N_{i,j,m}(q) \tag{1}$$

where $X_{i,j,m}(q)$ is the transmitted data in the qth subchannel, $N_{i,j,m}(q)$ is additive white Gaussian noise in that subchannel, and $H_{i,j,m}(q)$ is the channel frequency response in the qth subchannel between relay node i and relay node j at hop m. Let $\gamma_{i,j,m}(q)$ represent the instantaneous SNR of subchannel q from transmitting relay i to received relay j at hop m, $i,j = 1,...,L$, $m = 2,...,M-1$ and $q = 1,...,Q$. $\gamma_{S,j,1}(q)$ and $\gamma_{j,D,M}(q)$, $j = 1,...,L$, $q = 1,...,Q$, are the SNRs at hop 1 and M, respectively. With this model, we have $(M-2)L^2+2L$ i.i.d. links in the network.



Optimal Routing: Select the best path from L^{M-1} paths to minimize the end-to-end outage.

Ad-hoc Routing: Select the best relay at each hop to minimize the outage per hop. (a *joint selection is required at the last two hops)*

N-hop Routing: Select the best path from L^{N-1} paths to minimize the outage per N hops.

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

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 receiving relay at hop m in path i, $i = 1,...,W$ and $m = 1,...,M-1$. For convenience, let $r_0^{(i)}$ denote the source node and $r_M^{(i)}$ denote the destination node. Obviously each path has a different relay set $\{r_m^{(i)}\}$. For example, the path marked with the solid line in Fig. 1 chooses relay 1, 1 and L at hop 1, 2 and 3, and relay $L-1$ at hop $M-1$. Its relay set is then given by $\{1,1,L,...,L-1\}$.

In this paper, we focus on the end-to-end outage performance, which for path i, is given by

$$P_{out}^{(i)} = 1 - \prod_{m=1}^{M} (1 - P_{out,m}^{(i)}) \tag{2}$$

where $P_{out,m}^{(i)}$ is the outage probability at hop m of path i.

III. LINK QUALITY METRIC

In this section, we propose a link quality metric for coded OFDM systems. As described in Section II, each selected relay node will fully decode the received packet, re-encode it and forward it to the next relay cluster. Hard decision decoding is employed in each node, that is, the demodulation is first performed and then the error correction is executed. For a code which can correct d_c symbol errors, the entire OFDM block can be successfully decoded when there are less than d_c symbol errors after demodulation. For subchannel q of the link from transmitting relay i to received relay j at hop m, we assume the demodulation is correct when the SNR of this subchannel $\gamma_{i,j,m}(q)$ is greater than some SNR threshold γ_{th}, which can be determined as in [24]. According to these assumptions, we can measure the link quality in the following way. For the link at hop m of path i, $i = 1,...,L$, and $m = 2,...,M-1$, we sort the Q subchannels' SNRs and find the (d_c+1) th minimum value. We use this value to measure the link quality. Let $\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_{m},m}$ denote this SNR. If $\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_{m},m}$ is greater than the SNR threshold, less than d_c

demodulation errors will occur, that is, the entire block can be successfully decoded. Otherwise, the decoding will fail. In the following we will show that with this metric, (d_c+1)-order diversity can be achieved, if the Q subchannels are independent. This gives an upper bound on the diversity order.

The outage event at hop m of path i occurs when $\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}$ is less than γ_{th}. So, the outage probability at hop m of path i is

$$P^{(i)}_{out,m} = P(\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m} < \gamma_{th}) \tag{3}$$

With the assumption that the SNRs of Q subchannels are i.i.d. random variables, an outage occurs when more than d_c SNRs of the Q i.i.d. SNRs are less than γ_{th}, as gives

$$\begin{aligned} P^{(i)}_{out,m} = \sum_{j=d_c+1}^{Q} \binom{Q}{j} P(\gamma_{r^{(i)}_{m-1},r^{(i)}_m,m}(q) < \gamma_{th})^j \\ \times (1 - P(\gamma_{r^{(i)}_{m-1},r^{(i)}_m,m}(q) < \gamma_{th}))^{Q-j} \end{aligned} \tag{4}$$

where $\gamma_{r^{(i)}_{m-1},r^{(i)}_m,m}(q)$ represents the SNR of subchannel q (this could be any subchannel, because we assume the SNRs of the Q subchannels are i.i.d.). $\gamma_{r^{(i)}_{m-1},r^{(i)}_m,m}(q)$ is an exponential distribution random variable with mean γ_0, so (4) becomes

$$\begin{aligned} P^{(i)}_{out,m} = \sum_{j=d_c+1}^{Q} \binom{Q}{j} \left(1 - \exp\left(-\frac{\gamma_{th}}{\gamma_0}\right)\right)^j \\ \times \left(\exp\left(-\frac{\gamma_{th}}{\gamma_0}\right)\right)^{Q-j} \end{aligned} \tag{5}$$

Applying the Taylor series expansion of $exp(-\gamma_{th}/\gamma_0)$, we obtain

$$P^{(i)}_{out,m} \approx \sum_{j=d_c+1}^{Q} \binom{Q}{j} \left(\frac{\gamma_{th}}{\gamma_0}\right)^j \left(1 - \frac{\gamma_{th}}{\gamma_0}\right)^{Q-j} \tag{6}$$

But

$$\left(1 - \frac{\gamma_{th}}{\gamma_0}\right)^{Q-j} = \sum_{v=0}^{Q-j} \binom{Q-j}{v} \left(-\frac{\gamma_{th}}{\gamma_0}\right)^v \tag{7}$$

And (6) becomes

$$P^{(i)}_{out,m} \approx \binom{Q}{d_c+1} \left(\frac{\gamma_{th}}{\gamma_0}\right)^{d_c+1} + o\left(\left(\frac{\gamma_{th}}{\gamma_0}\right)^{d_c+1}\right) \tag{8}$$

where $o(x)$ means the remaining terms are small and approach zero. From (8), we can see that (d_c+1)-fold diversity gain is achieved.

IV. ROUTING STRATEGIES AND OUTAGE ANALYSIS

In this section, we will extend the three routing strategies in [1] to broadband OFDM systems. As discussed in Section III, an outage occurs when the (d_c+1) th minimum SNR of the Q subchannels, $\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}$, is less than the SNR threshold γ_{th}. So, the end-to-end outage of path i, $i = 1, ..., W$, will be

$$\begin{aligned} P^{(i)}_{out} &= 1 - \prod_{m=1}^{M} \left(1 - P\left(\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m} < \gamma_{th}\right)\right) \\ &= P\left(\min_{m=1,\ldots,M} \left\{\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}\right\} < \gamma_{th}\right) \end{aligned} \tag{9}$$

Obviously, the end-to-end outage of an M-hop path is limited by the worst hop. Compared with flat fading scenarios in [1], the only difference is that we use $\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}$ to measure the link quality.

A. Optimal Routing

As shown in (9), the end-to-end outage of path i is limited by the minimum SNR of the M hops, $\gamma^{(i)}_{\min} = \min_{m=1,\ldots,M} \left\{\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}\right\}$. Therefore, to minimize the end-to-end outage of the entire network, the path with the maximum $\gamma^{(i)}_{\min}$ should be chosen. So, in optimal routing strategy, we first find the minimum SNR of each path, then we compare these minimum SNRs and choose the path with the largest minimum SNR. The algorithm is then: provided below.

```
Given $L$ and $M$, let $W = L^{M-1}$.
Initialization:
Generate all possible paths $\{r^{(i)}_m\}$, $r^{(i)}_0 = S$,
$r^{(i)}_M = D$, $i = 1, ..., W$
$\gamma^{max}_{min} = 0$, $ind^* = 0$
Recursion:
For $i = 1 : W$
    Sort the $Q$ subchannels' SNRs of each relay node
    in path $i$
    Let $\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}$ represent the $(d_c+1)$ th minimum SNR
    at hop $m$
    Calculate $\gamma^{(i)}_{\min} = \min_{m=1,\ldots,M} \{\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}\}$ for all path $i$;
    If $\gamma^{(i)}_{min} > \gamma^{max}_{min}$
        $\gamma^{(i)}_{min} = \gamma^{max}_{min}$, $ind^* = i$;
    End if
End loop
Output the optimal path $\{r^{(ind^*)}_m\}$
```

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

$$P^{opt}_{out} = P\left(\max_{i=1,\ldots,W} \min_{m=1,\ldots,M} \left\{\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}\right\} < \gamma_{th}\right) \tag{10}$$

After some manipulation, and for sufficiently high SNR, we obtain the end-to-end outage of optimal routing

$$P^{opt}_{out} \approx \begin{cases} \left(2\binom{Q}{d_c+1}\left(\frac{\gamma_{th}}{\gamma_0}\right)^{d_c+1}\right)^L & M = 2 \\ 2\left(\binom{Q}{d_c+1}\left(\frac{\gamma_{th}}{\gamma_0}\right)^{d_c+1}\right)^L & otherwise \end{cases} \tag{11}$$

The derivation has been omitted for the sake of brevity. From (11), it can be seen that optimal routing can always achieve $L(d_c+1)$-order diversity. For high SNR, 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. Ad-Hoc Routing

The end-to-end outage is minimized with optimal routing. However, it requires channel information for 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 level of complexity. To reduce the amount of required information, an ad-hoc routing strategy was proposed in [1]. In ad-hoc routing, the relay selection is performed on a per-hop basis. Here, we re-design the ad-hoc routing strategy for broadband systems according to the proposed link quality metric. 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 $\gamma^{\dagger}_{r^*_{m-1},j,m}$ is selected. So, at hop $m=1,...,M-2$, $r^*_m = \arg\max_{j=1,\ldots,L}\{\gamma^{\dagger}_{r^*_{m-1},j,m}\}$, where r^*_{m-1} is the relay chosen at hop $m-1$ (let $r^*_0 = S$). This relay selection can be performed in a distributed way. At hop $M-1$, instead of selecting the one with the largest $\gamma^{\dagger}_{r^*_{M-2},j,m}$, a joint selection should be performed, i.e., $r^*_{M-1} = \arg\max_{j=1,\ldots,L}\min(\gamma^{\dagger}_{r^*_{M-2},j,M-1},\gamma^{\dagger}_{j,D,M})$. We will show that in this way $L(d_c+1)$-order diversity can be achieved. The details of ad-hoc routing are summarized below.

```
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 $m = 1 : M-2$
    Sort the $Q$ subchannels' SNRs of each relay node
    at hop $m$
    Let $\gamma^{\dagger}_{r^*_{m-1},j,m}$ represent the $(d_c+1)$ th minimum SNR
    of relay node $j$ at hop $m$
    $r^*_m = \arg\max_{j=1,\ldots,L}\{\gamma^{\dagger}_{r^*_{m-1},j,m}\}$;
End loop
$r^*_{M-1} = \arg\max_{j=1,\ldots,L}\min(\gamma^{\dagger}_{r^*_{M-2},j,M-1},\gamma^{\dagger}_{j,D,M})$
Output the optimal path $\{r^*_m\}$
```

In this case, the end-to-end outage for high SNR becomes

$$P^{ad}_{out} \approx (M-2+2^L)\left(\binom{Q}{d_c+1}\left(\frac{\gamma_{th}}{\gamma_0}\right)^{d_c+1}\right)^L \qquad (12)$$

From (12) it can be seen that ad-hoc routing can also achieve $L(d_c+1)$-order diversity. However, in contrast to optimal routing, the outage 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 was also proposed in [1]. Here we extend it to the broadband scenario. In N-hop routing, the optimal path is selected every N hops, i.e., $ind^*_j = \max_{i=1,\ldots,w_j}\min_{m=(j-1)N+1,\ldots,jN}\left\{\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}\right\}$, 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.

```
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 $j = 1 : T-1$
    Generate all the $w_j$ paths;
    Sort the $Q$ subchannels' SNRs of each relay node
    Let $\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}$ represent the $d_c+1$ th minimum SNR
    at hop $m$ in path $i$
    $ind^*_j = \max_{i=1,\ldots,w_j}\min_{m=(j-1)N+1,\ldots,jN}\left\{\gamma^{\dagger}_{r^{(i)}_{m-1},r^{(i)}_m,m}\right\}$,
    $r^{(i)}_{(j-1)N} = r^{(ind^*_{j-1})}_{(j-1)N}$;
    $R^*_j = \{r^{(ind^*_j)}_m\}$, $m = (j-1)N+1,...,min(jN,M)$.
End loop
Output the optimal path $\{R^*_1,...,R^*_T\}$.
```

For high SNR, the end-to-end outage of N-hop routing becomes, with $T=\lceil M/N\rceil$, and if $M-(T-1)N=2$

$$P^{N-hop}_{out} \approx (T-1+2^L)\left(\binom{Q}{d_c+1}\left(\frac{\gamma_{th}}{\gamma_0}\right)^{d_c+1}\right)^L \qquad (13)$$

otherwise

$$P^{N-hop}_{out} \approx (T+1)\left(\binom{Q}{d_c+1}\left(\frac{\gamma_{th}}{\gamma_0}\right)^{d_c+1}\right)^L \qquad (14)$$

From (13) and (14) it can be seen that N-hop routing also achieves $L(d_c+1)$-order diversity, 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 approaches that of ad-hoc routing. An appropriate N should be selected to achieve a good performance-complexity tradeoff. N should be chosen to ensure that $M-(T-1)N \geq 2$. At this time, N is determined through simulation. An analytical approach is the subject of current research.

V. SIMULATIONS 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 [24], that is, the SNR threshold is set as $\gamma_{th} = 2^r - 1$, where r is the spectral efficiency. In this paper, we assume $r = 2$ bit/s/Hz, which gives $\gamma_{th} = 3$. We assume there are 4 subchannels and a (4,2) linear block code is adopted. The block code can correct one symbol error, i.e., $d_c = 1$. So, the achievable diversity order is $2L$.

In Fig. 2, we provide the outage comparison of optimal routing, ad-hoc routing, and N-hop routing in a 4-hop network with $L = 2$ relay nodes in each relay cluster. With N-hop routing, the best path is selected every $N = 2$ hops. It can be seen that all three routing strategies can achieve the expected 4-fold diversity order. However, a 1-dB power gain is observed with optimal routing at an outage of 10^{-2} compared to ad-hoc routing. The outage performance of N-hop routing is similar to that of ad-hoc routing. Actually from (12) and (13) 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.

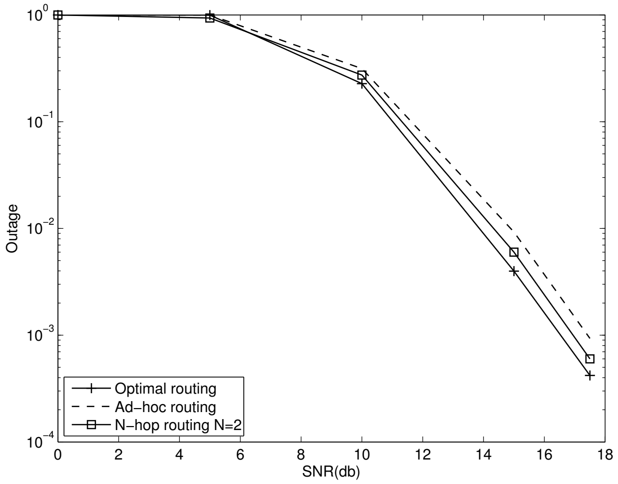


Fig. 2. Outage performance of optimal routing, ad-hoc routing and N-hop routing with $M = 4$ hops (L=2).

With an increase in M, the performance gain of N-hop routing over ad-hoc routing is clearly observed. As shown in Fig. 3, in an 8-hop network, the performance gaps of these three routing strategies increase compared to the 4-hop case. For example, 2-dB and 1.5-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 information and complexity level also increase.

Compared with the simulation results of the same size network in [1], we can see that the performance gaps among the three routing strategies has decreased. This is because in broadband system we can achieve a higher order diversity gain (L-order diversity in flat fading scenario [1] and $L(d_c + 1)$-order diversity in broadband systems).

VI. CONCLUSIONS

In this paper, we extend the proposed three routing strategies in [1] to broadband systems. We first propose a link quality metric for broadband wireless links; then, we re-design the three routing strategies according to this link quality metric. We demonstrated that optimal routing can achieve $L(d_c + 1)$-order diversity, and the performance does not deteriorate when the number of hops, M, increases. Ad-hoc routing can also achieve $L(d_c + 1)$-order diversity. However, the performance gap between optimal routing and ad-hoc routing increases with the number of hops. N-hop routing, where a joint optimization is performed every N hops, can achieve a good performance-complexity tradeoff. The outage analysis of these three routing strategies was verified by simulation results.

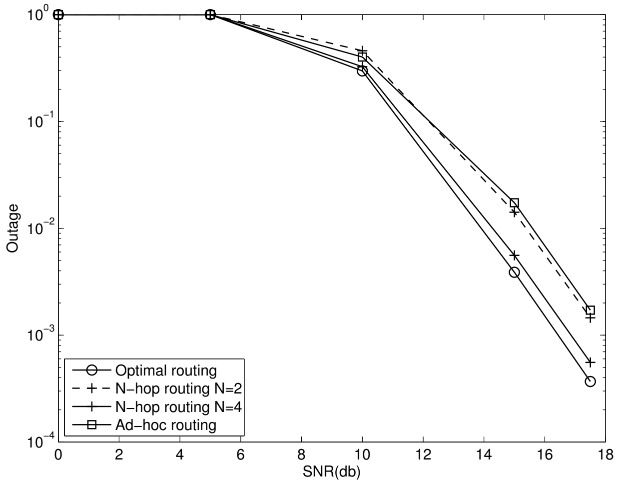


Fig. 3. Outage performance of optimal routing, ad-hoc routing and N-hop routing. M=8 hops and L=2.

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