Multihop Diversity - A Precious Source of Fading Mitigation in Multihop Wireless Networks

Lie-Liang Yang, Chen Dong and Lajos Hanzo
School of ECS, University of Southampton, SO17 1BJ, United Kingdom
Tel: 0044-(0)23-8059 3364, Email: llcy,cd2g09,lh@ecs.soton.ac.uk, http://www-mobile.ecs.soton.ac.uk

Abstract—The concept of multihop diversity is proposed, where all the nodes of a multihop link are assumed to have buffers for temporarily storing their received packets. During each time-slot, the best hop having, for example, the highest signal-to-noise ratio (SNR), is selected from the set of those hops, where the corresponding nodes have packets awaiting transmission in their buffer. The packet is then transmitted over the best hop. Explicitly, this hop-selection procedure yields selection diversity. In this paper, we assume having perfect channel knowledge and focus our attention on the principles and performance bounds of the error probability and outage probability, when M-ary quadrature amplitude modulation (MQAM) is employed. The error probability and outage probability of the multihop links operated under our proposed multihop diversity scheme are investigated, when communicating over Rayleigh fading channels. Our studies show that relying on multiple hops has the potential of providing a significant diversity gain, which may be exploited for enhancing the reliability of wireless multihop communications.

I. INTRODUCTION

In wireless multihop communications, source nodes (SNs) send information to the corresponding destination nodes (DNs) via intermediate relay nodes (RNs), which provides a range of advantages over conventional single-hop communications. Typically, these advantages may include an improved energy-efficiency and extended coverage, improved link performance, enhanced throughput, simplicity and high-flexibility of network planning, etc. [1–3]. Owing to their advantages, multihop networks have drawn a lot of attention and have been investigated from different perspectives, as evidenced by [1–11] and the references there in.

In the context of multihop links, it has typically been assumed that information is transmitted successively from a SN to a DN without any store-and-forward stage at the intermediate RNs [4, 5, 8]. For convenience, we refer to this scheme as the conventional multihop transmission scheme in our forthcoming discourse. In this conventional multihop scheme, information is transmitted over a hop during its scheduled time-slot, regardless of its link quality quantified, for example, by its signal-to-noise ratio (SNR). Hence, the overall reliability of a multihop link is dominated by that of the weakest hop and a route outage occurs, once an outage occurs in any of the hops invoked. As a result, the route error/outage performance of a multihop link usually degrades, as the number of hops increases. In order to improve the performance of multihop links, recently, some novel signaling schemes have been proposed [3, 12, 13], which require the nodes to have a store-and-forward capability. For example, in [12, 13], adaptive modulation and coding (AMC) combined with automatic repeat request (ARQ) schemes has been invoked in cooperative decode-and-forward (DF) communications. Very recently, the authors of [3] have employed AMC for dual-hop cooperative communications relying on a regenerative RN, where the AMC mode of both the hops may be configured independently.

In this contribution as well as in [14] for the BPSK case, we view the independently fading multiple hops of a link as an adaptively configurable resource that may be exploited for achieving a diversity gain. To the best of our knowledge, the multihop diversity concept, which exploits the independent fading of communication hops for attaining diversity, has never been investigated in the open literature. Multihop diversity may indeed be achieved, if every node of a multihop link has a buffer for temporarily storing the packets received. During a given time-slot, the highest-quality hop from the set of hops having packets in their buffers to send is activated to transmit, which hence results in selection diversity. Intuitively, the implementation of the proposed multihop diversity scheme requires global channel knowledge about all the hops. In this paper, however, we focus our attention on the basic principles and theoretical performance bounds under the idealized simplifying assumption that this global channel knowledge may be acquired, whenever required. Specifically, we study the error and outage performance of multihop links employing MQAM in Rayleigh fading channels, when either buffers of limited or unlimited size are used. Note that, the terminology of multihop diversity has also been used in [15]. However, the multihop diversity considered in [15] and that defined in this paper have different meaning. In [15], it is assumed that a receiving node can receive signals from several other nodes and hence the multihop diversity may be achieved at the receiving node by combining the signals received from the different nodes that transmitted the same information.

Our studies and performance results in this contribution demonstrate that independently fading multiple hops have the potential of providing significant diversity gain for improving the reliability of multihop communications. The error/outage performance can be improved, as the buffer size increases, and/or as the number of hops increases, provided that the SNR per bit is sufficiently high.

Note that, when transmitting a block of data, our multihop diversity scheme and the conventional multihop transmission scheme yield the same block delay. This is because the multihop diversity scheme transmits a single packet over a single hop per time-slot, identically to the conventional multihop transmission scheme.

II. SYSTEM MODEL OF MULTIHOP LINKS

Fig. 1. System model for a multihop wireless link, where SN S sends message to DN D via (L − 1) intermediate RNs.

The L-hop wireless link under consideration is shown in Fig. 1, which consists of (L + 1) nodes, one SN S (node 0), (L − 1) RNs \( R_1, R_2, \ldots, R_{L-1} \) and one DN D (node L). The SN S sends information to the DN D via L hops with the aid of the (L − 1) RNs, where all of them use the same MQAM modulation. At the RNs, the decode-and-forward (DF) protocol is employed for relaying the signals. The MQAM signal transmitted by the SN S (node 0) is denoted by \( x_0 \) and its estimate at the DN D (node L) is \( x_{L-1} \), while the MQAM signals estimated at the RNs are \( x_l \) for \( l = 1, \ldots, L - 1 \). It is assumed that \( E[|x_l|^2] = 1 \). When operated at packet level, these MQAM
signals are correspondingly represented by packet-length vectors \( \mathbf{x}_0, \mathbf{x}_i, i = 1, \ldots, K - 1 \), and \( \mathbf{x}_L = \mathbf{x}_0 \). In this paper, we assume that the signals are transmitted on the basis of time-slots having a duration of \( T \) seconds. The channels of the \( L \) hops are assumed to experience block-based independent flat Rayleigh fading, where the complex-valued fading envelop of a hop remains constant within a time-slot, but is independently faded for different time-slots. Based on the above assumptions, when the \( (l - 1) \)-th node transmits a packet \( \mathbf{x}_{l-1} \), the observations received by node \( l \) can be expressed as

\[
y_l = h_l \mathbf{x}_{l-1} + \mathbf{n}_l, \quad l = 1, 2, \ldots, L
\]

(1)

where \( h_l \) represents the channel gain of the \( l \)-th hop from node \( (l - 1) \) to node \( l \), while \( \mathbf{n}_l \) denotes the Gaussian noise at node \( l \). The channel gain \( h_l \) is assumed to be complex Gaussian with zero mean and \( \mathbb{E} |h_l|^2 = 1 \). The noise samples in \( \mathbf{n}_l, l = 1, \ldots, L \), obey the complex Gaussian distribution with zero mean and a common variance of \( \sigma^2 = 1/(2\gamma_l) \) per dimension, where \( \gamma_l \) denotes the received average SNR per hop. When related to the average SNR per symbol, \( \gamma_s \), and the average SNR per bit, \( \gamma_b \), the overall average SNR \( \gamma_l \) can be written as \( \gamma_l = \gamma_s/L = (m\gamma_b)/L \), where \( m = \log_2 M \) denotes the number of bits per symbol.

In this contribution, we focus our attention on the principles of multihop diversity and on the analysis of its performance, including both the BER and outage probability. The main assumptions adopted in our study are summarized as follows:

- The SN always has packets to send, hence the multihop link operates in its steady state.
- Both the SN and the RN can store an infinite number of packets. By contrast, each of the \( (L - 1) \) RNs can only store at most \( B \) packets.
- The fading processes of the \( L \) hops of the multihop link are independent, while the fading of a given hop remains constant within a packet duration or a time-slot, but is independently faded from one packet to another.
- There is a central control unit (CCU), which evaluates and exploits the global knowledge about the channels of the \( L \) hops. Based on the global channel knowledge of the \( L \) hops within a given time-slot, the CCU decides which of the nodes, \( 0, 1, \ldots, L - 1 \), transmits and also informs the corresponding receiver node without a delay and without errors. Note that, although this assumption is ideal, it is however not unreasonable. For example, for a two-hop link operated in time-division duplex (TDD) mode, the RN can act as the CCU to decide whether the SN or itself should transmit, since it has the channel knowledge of both the first and second hops. Similarly, efficient decision-making/sharing strategies can be designed for links with more than two hops.
- A receiver node employs ideal channel state information (CSI) for determining its decision.
- The received average SNR per hop in the context of the \( L \) hops is the same and it is denoted by \( \gamma_l \). Note that, this assumption is reasonable, even when both the propagation pathloss and the shadow fading are considered. This is because, in multihop communications, typically, power-assignment or power-control is used [17] to ensure that all hops have a similar average SNR and attain a similar reliability, so that the overall (or route) reliability of a multihop link is maximized [18].

Under the above assumptions, packets are transmitted over the multihop link based on the following strategy. Among those hops having at least one packet stored in their buffer awaiting transmission, the CCU first decides which is the most reliable hop according to the instantaneous SNR values. Then, one packet is transmitted over the most reliable hop using a time-slot. According to this strategy, packets are transmitted obeying the time-division principles and hence transmitting a packet from the SN to the DN requires in total \( L \) time-slots. Below we analyze the BER and outage probability of the multihop link using MQAM.

### III. Performance Analysis

In this section, we derive the lower-bounds for the BER and outage probability of the multihop link shown in Fig. 1. Based on Fig. 1 and on the operational principles of the multihop link, as described in Section II, the following events may occur, when every RN has a buffer of size of \( B \) packets. Firstly, the buffer of a RN may be empty at some instants. In this case, this RN cannot be the transmit node, since it has no data to transmit. Secondly, the buffer of a RN may be full at some instants. Then, this RN cannot be the receiving node, since it cannot accept another packets. In these cases the CCU has to select a hop for transmission from a reduced number of hops, which results in an increased BER and outage probability due to the reduced selection diversity gain. Therefore, the lower-bounds of the BER and the outage probability are derived by loosening the above-mentioned constraints and assuming that each RN has an unlimited buffer size and that a node always has packets to transmit, whenever it is instructed by the CCU to transmit.

#### A. Lower-Bound Bit Error Rate

In order to derive the lower-bound BER, we first derive the single-hop BER, \( P_{L,E} \), under the assumptions that every RN has an infinite buffer and that a node always has packets prepared to send. Then, the lower-bound of the end-to-end BER, \( P_{L,E} \), of the multihop link shown in Fig. 1 is derived. The subscript ‘L’ in \( P_{L,E} \) stands for the lower-bound.

First, for the time-slot considered, let us express the instantaneous SNR of the \( L \) hops as \( \{\gamma_1, \gamma_2, \ldots, \gamma_L\} \). Then, based on the above assumptions, the hop activated for transmission has the instantaneous SNR of

\[
\gamma = \max\{\gamma_1, \gamma_2, \ldots, \gamma_L\}
\]

(2)

where \( \gamma_l \) is given by

\[
\gamma_l = |h_l|^2\gamma_h, \quad l = 1, 2, \ldots, L
\]

(3)

when communicating over Rayleigh fading channels. The probability density function (PDF) of \( \gamma_l \) can be readily derived, which is \( f(\gamma_l) = \gamma_l^{L-1}e^{-\gamma_l/\gamma_h} \), \( l = 1, \ldots, L \). Furthermore, the PDF of \( \gamma \) defined in (2) is [19]

\[
f(\gamma) = \frac{d}{d\gamma} \left[ \int_0^\gamma f(\gamma')d\gamma' \right]_L
\]

\[
= \frac{L}{\gamma_h} \exp\left(\frac{-\gamma}{\gamma_h}\right) \left[ 1 - \exp\left(\frac{-\gamma}{\gamma_h}\right) \right]^{L-1}
\]

(4)

Based on the PDF \( f(\gamma) \), we now analyze the lower-bound single-hop BER \( P_{L,E} \), by first considering the conditional probability \( P_{L,E}(\gamma) \).

It is well-known that the MQAM signal can be decomposed into two independent PAM signals [19–21], each of which has the constellation points located at \( \pm d, \pm 3d, \ldots, \pm \sqrt{M-1}d \), where \( 2d \) represents the minimum Euclidean distance of the constellation points and, when normalized by the noise variance \( \sigma^2 \), \( d \) can be written as [19, 20]

\[
d = \sqrt{\frac{6\gamma_h}{2(M-1)}}
\]

(5)

In MQAM, the two constituent PAM signals have the same error probability and can be treated independently. For example, when the Gray coded bit mapping is assumed, which is the case considered in
this paper, the 64QAM constellation can be decomposed into the (I-)
PAM and (Q-)PAM as shown in Fig. 2, where \( b_{1}b_{2}b_{3} \) and \( b_{4}b_{5}b_{6} \) are the bits carried by the I-PAM and Q-PAM, respectively.

Let us now specifically consider the I-PAM and denote the probability that a transmitted signal belongs to the constellation point \( i \) as \( P_{i} \), where \( i = \pm 1, \ldots, \pm (\sqrt{M} - 1) \). Furthermore, let us denote \( P_{i,j} (\gamma) \) the probability of \( \gamma \) being transmitted, given that \( i \) was transmitted and \( e_{i,j} \) the number of different bits between the signals representing the constellation points \( i \) and \( j \). Then, the BER of MQAM can be expressed as

\[
P_{L,E} (\gamma) = \frac{2}{m} \sum_{i=-\sqrt{M}+1}^{\sqrt{M}-1} \sum_{j=-\sqrt{M}+1}^{\sqrt{M}-1} e_{i,j} P_{i,j} (\gamma)
\]

(6)

Let us define the vectors

\[
p = (P_{-\sqrt{M}+1}, P_{-\sqrt{M}+3}, \ldots, P_{\sqrt{M}-1})^{T}
\]

\[
P_{i,j} (\gamma) = \{ (P_{i,j} (\gamma)) \}, \quad E = \{ (e_{i,j}) \}, \quad I = [1, 1, \ldots, 1]^{T}
\]

(7)

where \( p \) is an \( \sqrt{M} \)-length vector, \( E \) is an \( \sqrt{M} \)-length vector with elements of ones, while \( P_{i,j} (\gamma) \) and \( E \) are square matrices of \( (\sqrt{M} \times \sqrt{M}) \) dimensional. Then, we can represent (6) as

\[
P_{L,E} (\gamma) = \frac{2}{m} p^{T} [E \otimes P_{i,j} (\gamma)] I = \frac{2}{m} p^{T} [E^{T} \otimes P_{i,j} (\gamma)] p
\]

(8)

where \( \otimes \) represents the Hadamard product \([22]\). Observe in (8) that, at the righthand side, only \( P_{i,j} (\gamma) \) depends on the SNR \( \gamma \). Hence, the average single-hop BER \( P_{L,E} \) can be obtained by averaging \( P_{L,E} (\gamma) \) of (8) with respect to the PDF of (4) as

\[
P_{L,E} = \int_{0}^{\infty} P_{L,E} (\gamma) f(\gamma) d\gamma = \frac{2}{m} \int_{0}^{\infty} \left( E^{T} \otimes \int_{0}^{\infty} P_{i,j} (\gamma) f(\gamma) d\gamma \right) p
\]

(9)

where \( P_{i,j} \) is the average transition probability from the constellation point \( i \) to the constellation point \( j \), given by

\[
P_{i,j} = \int_{0}^{\infty} P_{i,j} (\gamma) f(\gamma) d\gamma, \quad i, j = \pm 1, \pm 3, \ldots, \pm (\sqrt{M} - 1)
\]

(10)

As defined above, \( P_{i,j} (\gamma) \) is the transition probability that the receiver detects the \( j \)th constellation point, given that the \( i \)th constellation point was transmitted. This probability may be readily derived with reference to Fig. 2, which

\[
P_{i,j} (\gamma) = \begin{cases} Q \left( (i-j) - \frac{3}{2} \right), & \text{when } j = \pm (\sqrt{M} - 1) \\ Q \left( (i-j) - \frac{3}{2} \right) - Q \left( (i-j) + \frac{3}{2} \right), & \text{else} \end{cases}
\]

(11)

where \( Q(x) \) is the Gaussian Q-function, which can alternatively be defined [19] by \( Q(x) = \frac{1}{\sqrt{\pi}} \int_{0}^{x} e^{-x^2/4} dx \). For example, when 4QAM (QPSK) is employed, we have \( d/\sigma = \sqrt{7} \). Hence, based on (11), the probability transition matrix is given by

\[
P_{i,j} (\gamma) = \begin{bmatrix} 1 - Q \left( \sqrt{\gamma} \right) & Q \left( \sqrt{\gamma} \right) \\ Q \left( \sqrt{\gamma} \right) & 1 - Q \left( \sqrt{\gamma} \right) \end{bmatrix}
\]

(12)

Finally, when substituting (4), (5) and (11) into (10) and completing the integration, we arrive at

\[
P_{L,E} = \frac{L}{2} \sum_{l=0}^{L} \left( \frac{-1}{l+1} \left( L - 1 \right) \right) \left( 1 - \frac{A_{\gamma}^{2} g_{\gamma} b_{q}}{l+1 + A_{\gamma}^{2} g_{\gamma} b_{q}} \right)
\]

(14)

with \( g = 1.5/(M - 1) \). Consequently, the single-hop lower-bound BER of the \( L \)-hop links operated under the proposed multihop diversity principles can be evaluated by applying (13) into (9).

Having obtained the single-hop lower-bound BER \( P_{L,E} \), as shown in (9), the lower-bound end-to-end BER \( P_{L,E} \) can be obtained with the aid of the following approach. Let \( p_{L} \), \( l = 1, \ldots, L \), be an \( \sqrt{M} \)-length vector, which contains the \( \sqrt{M} \) average probabilities that the signal detected by the \( l \)th RN \( R_{l} \) belongs to the constellation points \( \{ \pm d, \pm 3d, \ldots, \pm 2(\sqrt{M} - 1)d \} \). Furthermore, let \( p_{L} \) be a vector containing single entry of one, while any of its other entries are zero. The location of the single one represents the specific constellation point transmitted. Then, from (8) and (9), we infer that

\[
p_{L} = (E^{T})^{-1} p_{0}
\]

(15)

which is a recursive equation. Hence, given that \( p_{0} \) transmitted, we have

\[
p_{L} = (E^{T})^{L-1} p_{0}
\]

(16)

which represents the (symbol) transition probability from \( p_{0} \) to \( p_{L} \) after \( L \) hops. Hence, when considering that there are \( \sqrt{M} \) possible transmitted symbols, which have the probabilities expressed by \( p_{L} \), as shown in (7), the lower-bound end-to-end BER of the \( L \)-hop link relying on our multihop diversity scheme can be represented by

\[
P_{L,E} = \frac{2}{m} \left( E^{T} \otimes (E^{T})^{L-1} \right) I = \frac{2}{m} \left( E^{T} \otimes (E^{T})^{L} \right) p
\]

(17)

In the first line of (17), \( I \) implies \( p_{0} \) in (16) associated with considering that there are \( \sqrt{M} \) different symbols.

For example, when 4QAM is considered, we readily infer the lower-bound end-to-end BER expression of

\[
P_{L,E} = \frac{1}{2} - \frac{1}{2} (1 - 2P_{L,E})^{L} = \frac{1}{2} - \sum_{n=0}^{L-1} (-1)^{n+1} 2^{n+1} P_{L,E}
\]

(18)

where the single-hop lower-bound BER \( P_{L,E} \) is given by

\[
P_{L,E} = \frac{L}{2} \sum_{l=0}^{L-1} \left( \frac{-1}{l+1} \left( L - 1 \right) \right) \left( 1 - \frac{\gamma}{2(l+1) + \gamma} \right)
\]

(19)

### B. Lower-Bound Outage Probability

The outage probability is the probability of the event that the maximal SNR of the \( L \) hops is lower than a pre-set threshold. When this event occurs, either no data is transmitted on the multihop link in order to guarantee the minimum required BER, or the BER becomes...
higher than a predicted value, if data is still transmitted. Given a threshold \( \gamma_T \), the lower-bound outage probability is given by

\[
P_{L,O} = \int_0^{\gamma_T} f(\gamma) d\gamma
\]  

(20)

When substituting (4) into this equation, we readily arrive at

\[
P_{L,O} = \left[ 1 - \exp \left( - \frac{\gamma_T}{\gamma_h} \right) \right]^L = \sum_{l=0}^{L} \left( -1 \right)^l \binom{L}{l} \exp \left( \frac{L \gamma_T}{\gamma_h} \right)
\]

(21)

which is simply the probability that each of the \( L \) hops has an SNR lower than \( \gamma_T \).

In contrast to the above multihop diversity scheme, in the conventional \( L \)-hop transmission scheme, an outage occurs, when one out of the \( L \) hops has an SNR below the threshold \( \gamma_T \). Therefore, the outage probability can be expressed as

\[
P_O = 1 - \left[ P(\gamma_l > \gamma_T) \right]^L = 1 - \left[ \int_{\gamma_T}^\infty f(\gamma) d\gamma \right]^L
\]

(22)

Upon applying the PDF of \( f(\gamma_l) \) into this equation yields

\[
P_O = 1 - \exp \left( - \frac{L \gamma_T}{\gamma_h} \right)
\]

(23)

Furthermore, it can readily be shown that we have

\[
\lim_{\gamma_h \to \infty} \log \left( \frac{P_{L,O}}{P_O} \right) = L
\]

(24)

which means that, if the SNR \( \gamma_l \) per hop is high, the outage probability of the \( L \)-hop diversity scheme decreases \( L \) times faster than that of the conventional \( L \)-hop transmission scheme. This property also explains that our proposed transmission scheme is capable of achieving an \( L \)-th order diversity.

**IV. Performance Results**

In this section, we provide both the BER and outage probability of multihop links employing various MQAM schemes, in order to illustrate the effect of the RNs’ buffer size on the achievable multihop diversity gain. In these figures, the lower-bounds were evaluated from the formulas derived in Section III, while the other results were obtained via simulations. For the sake of comparison, in these figures, the corresponding BER and outage performance results of the conventional multihop transmission scheme were provided. Furthermore, the single-hop BER and outage probability of 16QAM were depicted in Figs. 4 and 6, respectively. Note that the parameters used for generating the results were shown in the legends of the figures.

Fig. 3 illustrates the BER performance of the double-hop link, when it is operated either under the conventional or the proposed multihop diversity principles. When operated under the proposed multihop diversity principles, two scenarios were considered, namely the case where each RN had a buffer of size \( B = 24 \) and the case of having infinite buffers. From Fig. 3, we can observe that a substantial diversity gain is achievable, even for double-hop links. Taken 16QAM as an example, when the RN employs a moderate buffer size of \( B = 24 \), about 7 dB SNR gain is achievable at the BER of 0.002. When further increasing the buffer size, the diversity gain may be as high as 11 dB at the BER of 0.002. These trends are also verified by the results in the following figures.

In Fig. 4, we demonstrate the effect of both the number of hops and of the RN’s buffer size on the achievable multihop diversity gain. Observe that the multihop diversity gain improves, as the number of hops and the RN’s buffer size are increased, if the average SNR per bit is sufficiently high. However, at a given SNR per bit value, there is a specific number of hops, which yields the highest diversity gain. As seen in Fig. 4, for \( B = 32 \), at \( \gamma_b = 15 \) dB, two-hop transmission constitutes the best option, while at \( \gamma_b = 18 \) dB, four-hop transmission may be used to achieve the best BER performance. By contrast, when the number of hops is fixed, the multihop diversity gain always increases, as the RN’s buffer size increases. Note that, in this contribution, no large-scale fading is considered and our studies are based on the assumption that the total received energy per symbol is independent of the number of hops. It is this assumption that leads to the above-mentioned observation in terms of the effect of the number of hops on the multihop diversity gain. If the large-scale fading is considered by taking into account of the propagation pathloss, the multihop diversity gain always improves, as the number of hops increases.

Figs. 5 and 6 characterize the outage probability of the multihop links, when various MQAM schemes, various buffer sizes and various number of hops are considered. Again, the outage probability of the corresponding conventional multihop transmission scheme is provided for the sake of comparison. Note that, in our numerical computations and simulations, the threshold \( \gamma_T \) was adjusted to maintain a BER of 0.01 for a single-hop link. From the results of Figs. 5 and 6, we can draw similar conclusions, as those drawn from Figs. 3 and 4. A significant multihop diversity gain is attainable, when the RNs employ...
buffers of a sufficiently high size. The diversity gain increases, as the number of hops increases, provided that the SNR per bit is sufficiently high. Consequently, as seen in Figs. 5 and 6, the multihop diversity transmission scheme proposed in this contribution significantly outperforms its conventional multihop counterpart [8, 16].

Our future research will consider the multihop diversity gain under practical constraints of realistic propagation channels. Furthermore, the packet delay characteristics and wireless networking aspects of multihop diversity assisted wireless systems will be addressed.

REFERENCES


V. CONCLUSIONS

In this contribution, we have proposed and investigated a multihop diversity scheme. Both the BER and outage probability of multihop links have been investigated, when assuming that MQAM signals are transmitted over Rayleigh fading channels. Our analysis and performance results show that exploiting the independent fading of multiple hops results in a significant diversity gain. The proposed multihop diversity scheme significantly outperforms its conventional multihop counterpart in terms of the attainable BER/outage performance, when sufficiently large buffers are considered. In general, the multihop diversity gain increases as the RNs’ buffer size increases. The multihop diversity gain can also be improved as the number of hops increases, provided that the SNR is sufficiently high.

---

**Fig. 5.** Outage probability versus $\gamma_n$ of the average SNR per bit for the double-hop links with various MQAM schemes, when communicating over Rayleigh fading channels.

**Fig. 6.** Outage probability versus $\gamma_n$ of the average SNR per bit for the multihop links with various number of hops and various buffer size, when communicating over Rayleigh fading channels.