Information Efficiency of Multihop Packet Radio Networks With Channel-Adaptive Routing

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***Abstract*—This paper analyzes the benefit of adaptive routing based on knowledge of the channel state information in multihop, ad hoc wireless networks that use direct-sequence code-division multiple access. Cross-layer, channel-adaptive routing exploits the inherent spatial diversity of multihop wireless networks to select links with favorable channel conditions. The *information efficiency*, an extension of a previously used measure called expected progress, is used to evaluate performance. Results show that, combined with adaptive modulation, adaptive routing can improve performance in ad hoc networks by a factor of four to five in channels with Rayleigh fading and lognormal shadowing. The lack of position information in the routing decision would reduce performance by 25%. New approaches to channel-adaptive routing that enable rapid adaptivity to channel conditions are discussed.**

***Index Terms*—Ad hoc, adaptive routing, cross-layer, information efficiency, multihop, packet radio.**

I. Introduction

COMMON to most wireless networks, including multihop ad hoc networks, is the challenge of communicating over links that experience multipath fading, shadowing, large-scale path loss, and interference from other transmissions. Compounding these effects is their variability in time. The mobility of either the transmitting or receiving node, or of reflectors in their path, can lead to large fluctuations in signal strength due to fading. Thus, while a particular link on a multihop route may be available at one time, at a later time, it may experience an outage. Potentially, even more dynamic in a packet radio network is the interference, which can change dramatically in a short time due to the bursty nature of many data applications.

Notwithstanding these challenges, multihop networks present unique opportunities that can be exploited to mitigate the effects of variable link conditions and even benefit from them. In particular, these networks offer rich opportunities for increasing efficiency through a combination of spatial and temporal diversity. The availability of temporal diversity is not unique to multihop networks, as single-hop networks in mobile environments can also benefit from temporal diversity through increased coding gain or adaptive transmission. However, multihop networks offer an added dimension of spatial diversity through alternate routes. Illustrating this, Fig. 1 depicts an example of a source and destination with three alternative two-hop routes between them. Like multiple antennas at either node, the spatial diversity provided by these routes can be used to combat small-scale fading. However, unlike multiple antennas, alternate routes can also be used to combat the attenuation due to shadowing, which is on a larger scale than multi-element antenna spacing. For example, obstructions causing high attenuation on a given link can be circumvented by following a different path. Furthermore, with knowledge of the channel state, performance can be improved by utilizing links that experience constructive multipath fading. Constructive fading can be exploited to reduce energy consumption through power control or increase the data rate through adaptive modulation, provided the fading rate is such that the transmitter can react to it in a timely manner.[1]

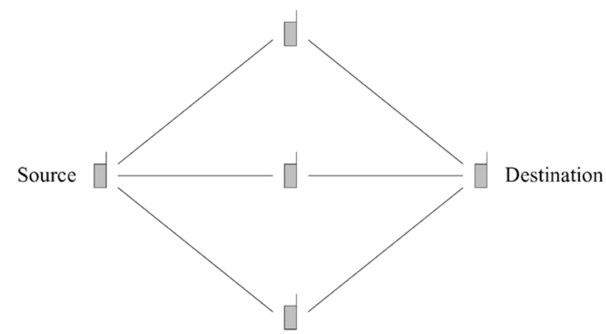

Fig. 1. Alternate two-hop routes between a source and destination.

Motivated by the spatial and temporal diversity of multihop packet radio networks, this paper investigates the use of channel-adaptive routing to exploit this diversity and improve system performance. Channel-adaptive routing uses channel state information (CSI) and cross-layer integration to route traffic along higher capacity paths, achieving a type of spatial waterfilling. As with other types of waterfilling, by consistently selecting those channels that have more favorable conditions at any given time, overall system throughput can be increased. This paper proposes new approaches to channel-adaptive routing that enable rapid adaptivity at the network layer to changes in channel state at the physical layer. It then analyzes the potential gains in information efficiency, which is a measure of multihop system performance based on link parameters, for various forms of adaptive routing.

[1]Higher rates of fading would presumably provide sufficient diversity in time to render the need for spatial diversity less critical.

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The remainder of the paper is organized as follows. Section II describes a family of ad hoc network routing protocols that would be particularly well-suited to CSI-based adaptive routing. The system model is defined in Section III. Section IV presents an analysis of various adaptive schemes that differ in the type of information utilized (i.e., CSI and position information). Quantitative results are given in Section V, and Section VI summarizes the key conclusions.

II. Channel-Adaptive Per-Hop Routing

Conventional routing protocols for ad hoc networks establish an end-to-end route between a source and destination, either through table updates or on-demand when a route is needed, and traffic traverses the same route as long as it is available. With some exceptions, most ad hoc network routing protocols are not designed to rapidly adapt to and exploit changes in link quality. Signal stability-based adaptive routing [1] includes means for measuring the signal strength of links, characterizing them as "strong" or "weak," and favoring strong links in route discovery, but provides no mechanism for proactively updating routes in response to changes in channel state. Bandwidth guarded channel adaptive (BGCA) routing [2] and receiver-initiated channel adaptive (RICA) routing [3] select and update routes in response to channel conditions, but because updates are based on an end-to-end CSI-based metric, the responsiveness of these protocols to changes in channel state is limited. Furthermore, the periodic end-to-end transmission of "CSI-checking" packets in RICA, and the route maintenance required for BGCA, incur significant routing overhead. To facilitate channel-adaptive routing, other classes of protocols are required which can more rapidly respond to channel state variations with limited overhead.

One way to facilitate CSI-based routing is to provide multiple next-hop alternatives to a transmitting node, whether it be a source node or an intermediate node along the path to the destination. Each time a packet is forwarded, one of these next-hop links would be selected based on current channel conditions. Two classes of routing protocols that can be used in practice to provide such alternatives on a per-hop basis are position-based routing and multipath routing.

A. Position-Based Routing

Position-based (or location-aided) routing algorithms utilize knowledge of the geographic locations of the final destination and neighboring nodes to make a local, one-hop routing decision [4]. In general, a node transmits to a next-hop relay that offers progress toward the final destination. For example, for the sample topology in Fig. 2, node S with a packet destined for node D would transmit to M_1, M_2, or M_3. Such geographically greedy routing is often supplemented with strategies for avoiding dead-end routes and guaranteeing delivery. Location information can be obtained by global positioning system (GPS) receivers, if available, or through the exchange of relative coordinates obtained using signal strength or time of arrival radio location techniques [5]. Provided the node density or transmission range is large enough, a given transmitting node can learn of several candidate next-hop nodes using position-based routing.

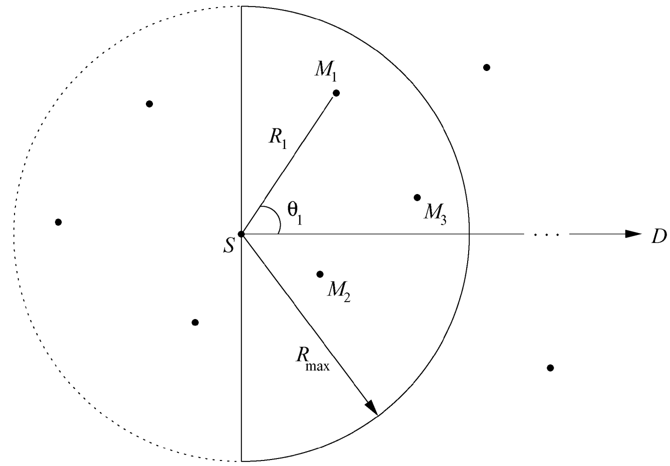

Fig. 2. Sample topology of a transmitter and three potential relay nodes.

Previously proposed criteria for selecting a relay node include *most forward within radius* R (MFR) and *nearest with forward progress* (NFP). MFR selects the relay providing the greatest forward progress toward the destination within some maximum radius R [6] (e.g., node M_3 in Fig. 2), with the aim of minimizing the total number of hops. NFP selects the closest relay offering forward progress [7] (e.g., node M_2 in the figure), with the aim of minimizing transmission power. These protocols are based on position information alone and ignore link quality. With a channel-aware adaptive routing scheme, nodes would track the channel quality on links to potential relays and would choose that relay among the alternatives which has the best channel conditions or offers the greatest *expected* progress toward the destination.

Depending on the type of channel adaptivity, channel measurements may take the form of signal-to-interference ratios (SIRs) or simply signal strength measurements. In single-frequency networks that use some form of time-division duplex, the signal attenuation on a bidirectional link (the combined path loss, shadowing and fading) is symmetrical. Hence, link attenuation measurements may be made either by the relay and fed back to the transmitting node or by the transmitting node listening to the control or data transmissions of the relay. Factors affecting the accuracy of link attenuation measurements include pilot overhead, the signal-to-noise-and-interference ratio, the mobility of the channel, and measurement delay.

Channel-adaptive selection of a relay can also be implemented in a manner that does not require knowledge of the channel state. In analogous fashion to selection diversity forwarding [8], multiple relays can simultaneously attempt to receive the transmission, and a relay that successfully decodes it forwards the packet on its next hop. If more than one relay successfully decodes, the selection of the forwarding relay can be based on position information, if available, or on some self-selecting method. One drawback of this scheme is that a given transmission occupies multiple relays that, using an appropriate access scheme, might otherwise serve as relays for other traffic. Nevertheless, such an approach may be more practical when channel measurement is difficult or inaccurate. In addition to more efficient relaying, another advantage of explicit knowledge of the channel state is the potential for

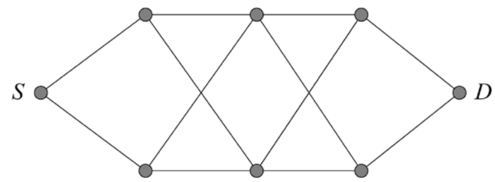

Fig. 3. Example of a mesh of multiple paths between a source and destination.

combining adaptive routing with adaptive modulation, that is, selecting one of a set of available modulation-coding schemes such that link throughput is maximized.

B. Multipath Routing

A second class of protocols that can be used adaptively is end-to-end route discovery algorithms modified to provide multiple routes between a source and destination. These algorithms do not require position information but rely instead on neighbor information exchange to establish routes that minimize some cost metric, such as the number of hops.

In their standard form, on-demand route discovery protocols create a single route between a source and destination. However, modifications to the ad hoc on-demand distance-vector (AODV) protocol, for example, have been proposed in [9] and [10] that would provide alternative next-hops along the route. These modified AODV protocols can be used to establish a mesh of multiple paths between the source and destination as illustrated in Fig. 3. In this example, there are six intermediate nodes between the source and destination, and each node two or more hops away from the destination has two next-hop alternatives with which to reach the destination. While originally intended to provide backup routes or to enable load balancing among different routes, such multipath routing algorithms can be coupled with channel-adaptive routing. Each node which has multiple next-hop alternatives would measure the channel state on those links, tracking changes due to mobility. A node would then forward a packet on the link that has the best channel conditions at that time.

In summary, per-hop routing, whether based on position information or derived from multipath route discovery, can be used to enable responsive channel-adaptive routing. The following section describes a system model for the analysis of such per-hop adaptive routing schemes.

III. System Model

As in previous work [11]–[13], a multihop packet radio network is modeled as a set of randomly, uniformly distributed nodes with average density λ nodes per unit area. Equivalently, nodes are distributed according to a two-dimensional (2-D) Poisson point process with parameter λ. The system utilizes a single carrier frequency, is slotted in time, and a node transmits a frame in a slot with probability p. Transmissions are made using direct-sequence/code-division multiple access (DS/CDMA), modeled with random spreading and chip asynchronism, and the network is assumed to be interference-limited. The average transmitted energy per symbol is the same for all nodes. Signal attenuation is a combination of large-scale path loss with distance (with path loss exponent m), medium-scale shadowing, and small-scale frequency-flat fading, and the overall attenuation is assumed to be constant during a slot.

Strong forward error correction is assumed, for which the probability of error is a steep function of the signal-to-noise ratio (SNR), such as would be obtained with iterative (turbo) decoding of concatenated codes. As a result, the probability of successful transmission of a frame is modeled as the probability that the SNR during the slot exceeds a threshold

$$P_s = \Pr[\mathrm{SNR} > \mu_c] = 1 - F_\mu(\mu_c) \tag{1}$$

where $F_\mu(\cdot)$ is the cumulative distribution function of the SNR and μ_c is the threshold or cut-off SNR. The cut-off value, in turn, is a function of the modulation-coding scheme.

In general, packets are transmitted in several hops from the source to the destination. A uniform traffic matrix is assumed (that is, the destination of any given source node's traffic is equally likely to be any other node in the network). On any given hop, the transmitting node selects a next-hop relay giving positive forward progress toward the destination within some maximum radius $R_{\max}$ representing the maximum transmission range of the transmitter. At least one relay with positive forward progress is assumed to be available. In Fig. 2, for example, the transmitting node S chooses to transmit to one of three relay nodes, M_1, M_2, or M_3, in the direction of the final destination D. The position of each node is described by its distance from the source R_i and the angle it makes with the final destination θ_i. The progress of a successful transmission is defined as the distance covered by that link toward the final destination, namely, $R_i \cos\theta_i$.

For a link distance of R_i, the parameter N_i is defined as

$$N_i \triangleq \lambda \pi R_i^2.$$

Hence, N_i is a dimensionless measure of the distance to relay i, interpreted as the average number of nodes within the transmission radius, R_i. Similarly, $N_{\max} \triangleq \lambda\pi R_{\max}^2$.

Given that a node is located within radius $R_{\max}$ of the source, the probability it lies within some smaller radius $r < R_{\max}$ is simply the ratio of the area of the smaller circle to the area of the larger circle. That is, the cumulative distribution function of the distance from the source to a relay randomly located within radius $R_{\max}$ is

$$\begin{aligned} F_R(r) &= \Pr[R \le r] \\ &= \frac{\pi r^2}{\pi R_{\max}^2}; \quad 0 < r < R_{\max}. \end{aligned}$$

Consequently, the corresponding parameter N of a relay in range of a source is uniformly distributed on $(0, N_{\max})$. Furthermore, the angle θ of a relay is independent of N and, due to the forward progress assumption, is uniformly distributed on $(-\pi/2, \pi/2)$.

Performance is measured in terms of the *information efficiency*, defined as the product of the progress (in distance) made by the transmission toward the final destination and the local throughput on the link, where the throughput incorporates the spectral efficiency of the modulation-coding scheme [13],

[14]. Maximizing the information efficiency balances the need to minimize the number of hops along a route with the need to maximize the throughput on a given hop, a key tradeoff inherent to multihop wireless networks. For the described system, the information efficiency (IE), normalized by the square root of the node density, is [13]

$$\mathrm{IE}(N,\theta) = \sqrt{\frac{N}{\pi}}\cos\theta\tau(p)\epsilon P_s \tag{2}$$

where $\tau(p) = (1-p)(1-e^{-p})$ is the probability that a local transmitting node and receiving node pair up[2] [11], ϵ is the spectral efficiency in bits per second per Hertz of the modulation-coding scheme, and the factor $\sqrt{N/\pi}\cos\theta$ is the normalized progress of the link. When multiplied by the system bandwidth and divided by the square-root of the node density ($\sqrt{\lambda}$), the IE has units of bit-meters/sec.

For a transmission to a given relay, the conditional IE, conditioned on that relay's position (specified by N and θ), and its fading attenuation (γ) is

$$\mathrm{IE}(N,\theta,\gamma) = \sqrt{\frac{N}{\pi}}\cos\theta\,\tau(p)\epsilon[1 - F_{\mu\,|\,\mathcal{C}}(\mu_c\,|\,\gamma)] \tag{3}$$

where $F_{\mu\,|\,\mathcal{C}}(\cdot\,|\,\gamma)$ is the distribution of the SIR at the receiver conditioned on the fading/shadowing attenuation $\mathcal{C} = \gamma$.

IV. Analysis

A framework is presented here for the analysis of three types of adaptive routing: attenuation adaptivity, position adaptivity, and the combination of the two. First, the distribution of the SIR is given. A special case is presented for which a closed-form expression of the average IE exists. Finally, the joint use of adaptive routing and adaptive modulation is considered.

A. SIR Distribution

To obtain the distribution function of the SIR, we first characterize the distribution of the interference energy. For the described system, the interference at a receiver during a given slot depends on a number of factors, including the positions of the active transmitters relative to the receiver, their channel gains to the receiver, and their chosen modulation schemes. The interference varies from slot to slot based on the set of nodes actively transmitting during the slot, their positions, etc. The distribution of the interference, therefore, must capture the variability of the set of transmitters and their positions, the statistics of the channel gain, and the probability distribution of the modulation schemes in use (to model adaptive modulation, for example).

Building upon the models in [15] and [16], the distribution function of the interference energy for the given system can be shown to have a stable distribution with index of stability inversely proportional to the path loss exponent m and having a dispersion parameter that is a function of system parameters, including interferer node density, processing gain, and chip pulse shape. For example, for a path loss exponent of $m = 4$, the distribution function of the interference energy was given as [17]

$$F_V(v) = \mathrm{erfc}\left(\frac{\sigma_Y}{\sqrt{2v}}\right); \quad v > 0 \tag{4}$$

where

$$\sigma_Y = \pi\sqrt{\frac{\pi}{2G}}\mathrm{E}[\sqrt{\mathcal{C}_i}]\delta\chi\lambda p \tag{5}$$

G is the processing gain, and $\mathrm{E}[\sqrt{\mathcal{C}_i}]$ is the mean amplitude of the fading attenuation of a generic interferer. The factor δ is a function of the chip pulse shape and the statistics of the relative chip delay of a generic interferer. It is given in general in [17], but for rectangular chips and uniformly distributed chip delay, $\delta \cong 0.8116$. The factor χ in (5) is a function of the statistics of the relative phase of a generic interferer and the modulation schemes in use in the network. Once again, the general expression is given in [17] but for a typical mix of 2-D constellations [e.g., quaternary phase-shift keying (QPSK), and M-quadrature amplitude modulation (QAM)] and uniformly distributed phase difference $\chi \cong 0.9601$.

For fourth-power path loss with distance, the SIR at the receiver for a link of distance R is given by $\mu = \mathcal{C}/(R^4 V)$, where V is the interference energy and $\mathcal{C}$ is the fading attenuation on the link. The conditional distribution of the SIR, conditioned on the channel attenuation, is then obtained from (4) as

$$F_{\mu\,|\,\mathcal{C}}(\mu'\,|\,\gamma) = \mathrm{erf}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu'}{2\gamma}}\right); \quad \mu' > 0 \tag{6}$$

where $\beta \triangleq \sigma_Y/(\lambda p)$.

For ease of presentation, the analysis below is presented with no loss of generality for the special case of $m = 4$ (fourth-power path loss with distance). It can be extended in straightforward fashion for any $m > 2$ using the more general expression for the distribution of the interference energy given in [17].

The adaptive schemes described in the remainder of this section affect the local destination of a given interferer's transmission, and, in the case of adaptive modulation, the choice of modulation scheme for that transmission, as well. However, they do not involve the scheduling of these transmissions. Therefore, the assumption of a Poisson field of interferers is maintained and the preceding interference model holds. The statistical distribution of the modulation scheme selection, made independently by each transmitting node based on the channel gain to its respective destination, is incorporated into the interference model through the factor χ in (5).

B. Attenuation and Position Adaptivity (APA)

Beginning with the most adaptive of the three forms of adaptive routing, APA selects the next-hop relay that maximizes the IE toward the destination based on knowledge of both the channel attenuation on each relay link as well as the position of each relay. The channel attenuation, here, is the combined effect of path loss due to transmitter–receiver distance and fading/shadowing on the link. Because of its reliance on position information, APA would be a candidate for use

[2]The probability that two nodes pair up is defined as the probability that the transmitter transmits in the given slot, the receiver is idle during that slot, and the receiver attempts to receive that transmission among other possible concurrent transmissions.

in systems utilizing position-based routing. The algorithm for relay selection with APA routing is the following.

1) Collect the position (R_l, θ_l) and link gain of each candidate relay.
2) Select the relay that maximizes (3).

To obtain the performance of APA routing, let L be the number of alternative relays available to the transmitting node on a given hop, and let $(N_l, \theta_l, \mathcal{C}_l)$ specify the position and fading attenuation of relay $l, 1 \leq l \leq L$. Then, for APA, the conditional IE of a given transmission is just the maximization of (3) over l

$$\mathrm{IE}_{\mathrm{APA}}(\mathbf{r}) = \frac{\tau(p)\epsilon}{\sqrt{\pi}} \max_{1\leq l\leq L} \left\{ \sqrt{N_l}\cos\theta_l \mathrm{erfc}\left(\frac{\beta N_l p}{\pi}\sqrt{\frac{\mu_c}{2\gamma_l}}\right)\right\} \quad (7)$$

where (6) was used for the conditional distribution of the SIR and where $\mathbf{r}$ is a vector of $3L$ random variables representing the position and fading attenuation of all L relays

$$\mathbf{r} = [N_1 \quad \theta_1 \quad \mathcal{C}_1 \quad \cdots \quad N_L \quad \theta_L \quad \mathcal{C}_L].$$

As mentioned earlier, due to the assumption of randomly, uniformly distributed nodes, the N_l are independent identically distributed (i.i.d.), uniform on $(0, N_{\max})$ and the θ_l are i.i.d., uniform on $(-\pi/2, \pi/2)$, and independent of the N_l. The joint distribution of the $\mathcal{C}_l$ is a function of the fading/shadowing model. The average IE is the expectation of the above over $\mathbf{r}$

$$\mathrm{IE}_{\mathrm{APA}} = \mathrm{E}_{\mathbf{r}}[\mathrm{IE}_{\mathrm{APA}}(\mathbf{r})]. \quad (8)$$

This expectation represents a $3L$-fold integral with the density of $\mathbf{r}$ or equivalently, the three-fold integral with the joint density of the set of random variables $(N_l, \theta_l, \mathcal{C}_l)$ for that l that maximizes (7). While specific results for (8) are obtained numerically, a special case which leads to a closed-form solution is discussed later in this section.

C. Attenuation Adaptivity (AA)

AA selects the next-hop relay that maximizes the IE *presuming knowledge of the link attenuation only* and no knowledge of the relay position. Comparing this type of adaptivity with APA will shed light on the value of position information in adaptive routing. The algorithm for relay selection with AA routing is simply the following.

1) Measure the link gain of each candidate relay.
2) Select the relay with the maximum link gain.

The conditional IE of a given transmission using attenuation adaptivity is similar to (7), except that the factor requiring position information $\sqrt{N_l}\cos\theta_l$ is moved outside of the maximization

$$\mathrm{IE}_{\mathrm{AA}}(\mathbf{r}) = \sqrt{\frac{N_j}{\pi}}\cos\theta_j \tau(p)\epsilon \mathrm{erfc}\left(\frac{\beta N_j p}{\pi}\sqrt{\frac{\mu_c}{2\gamma_j}}\right) \quad (9)$$

where

$$j = \arg\max_l \left\{ \mathrm{erfc}\left(\frac{\beta N_l p}{\pi}\sqrt{\frac{\mu_c}{2\gamma_l}}\right)\right\} = \arg\max_l \left\{\frac{\gamma_l}{N_l^2}\right\} \quad (10)$$

and where the second line is due to the monoticity of the complementary error function. In other words, j is the index of the relay with maximum overall link attenuation γ_l/R_l^4 (where R_l^4 is contained in N_l^2). As before, the average IE is then the expectation of (9) with respect to $\mathbf{r}$.

D. Position Adaptivity (PA)

The third form of adaptive routing considered here is based on position information only and not on CSI. With PA the transmitter selects the relay offering the greatest potential forward progress; thus, it is equivalent to the MFR position-based routing scheme. This form of adaptive routing is included in the analysis for comparison with the above two CSI-based approaches.

The algorithm for relay selection with PA routing is the following.

1) Collect the position (R_l, θ_l) of each candidate relay.
2) Select the relay offering the maximum forward progress $R_l \cos\theta_l$.

The conditional IE of a given transmission using position adaptivity is analogous to (9) except that, here

$$j = \arg\max_l \{\sqrt{N_l}\cos\theta_l\}. \quad (11)$$

The preceding selection criterion represents a basic version of position adaptivity, neglecting the impact of position on the probability of success of the transmission. The effect is that relays offering large progress are favored even though those links tend to experience greater attenuation and therefore lead to a lower probability of success. Despite lack of knowledge of the link attenuation in this case, the selection rule can be extended to account for the probability of successful transmission by first averaging (9) over the fading distribution and then selecting that relay whose position maximizes the resulting expression for the IE. For example, for Rayleigh fading channels, where $\mathcal{C}$ is exponentially distributed, the conditional probability of success averaged over the fading is

$$P_s = \int_0^\infty \mathrm{erfc}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu_c}{2\gamma}}\right) e^{-\gamma}\, d\gamma = \exp\left(-\frac{\beta N p}{\pi}\sqrt{2\mu_c}\right); \quad \mu' > 0 \quad (12)$$

where the second line was obtained using [18, (6.284)]. The resulting selection rule, then, is

$$j = \arg\max_l \left\{\sqrt{N_l}\cos\theta_l \exp\left(-\frac{\beta N_l p}{\pi}\sqrt{2\mu_c}\right)\right\}.$$

Alternatively, a simpler though suboptimal selection rule for more general fading scenarios utilizes the conditional probability of success with $\gamma = 1$

$$j = \arg\max_l \left\{\sqrt{N_l}\cos\theta_l \mathrm{erfc}\left(\frac{\beta N_l p}{\pi}\sqrt{\frac{\mu_c}{2}}\right)\right\}. \quad (13)$$

The above rule was observed to perform nearly identically to the optimum for the case of Rayleigh fading. Selection rule (13) represents an improvement over MFR and is referred to in the discussion of results below as "extended" position adaptive routing versus "basic" PA routing which uses selection rule (11).

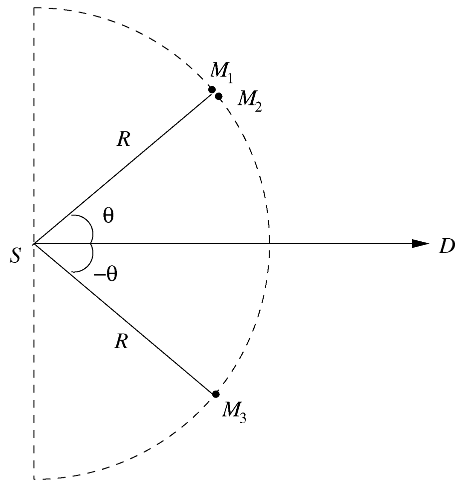

Fig. 4. Scenarios with constant $(N, |\theta|)$.

E. Special Case

In each case above, the average IE is an expectation over a nontrivial multivariate joint density, and a closed-form solution for the average IE is difficult to obtain, in general. However, a closed-form solution is readily obtained for a special case in which $(N_l, |\theta_l|)$ are constant for all l, and the fading is Rayleigh distributed. This case provides insight into the impact of the route diversity order L, as well as other parameters.

As depicted in Fig. 4, this special case applies to scenarios in which a cluster of two or more relays are very close together (e.g., M_1 and M_2 in the figure) or in which two relays (or two clusters) are positioned symmetrically with respect to the final destination (e.g., M_1 and M_3 in Fig. 4).

Since N_l and $|\theta_l|$ are constant over l in this case, the forward progress is constant, and the two CSI-based schemes APA and AA are equivalent. The conditional IE is similar to (7) except the constant factor $\sqrt{N}\cos\theta$ can be moved outside of the maximization, so that

$$\begin{aligned}\mathrm{IE}_{\mathrm{AA,sc}}(\boldsymbol{\gamma}) &= \sqrt{\frac{N}{\pi}}\cos\theta\tau(p)\epsilon \\ &\quad\cdot \max_l\left\{\mathrm{erfc}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu_c}{2\gamma_l}}\right)\right\} \\ &= \sqrt{\frac{N}{\pi}}\cos\theta\tau(p)\epsilon \\ &\quad\cdot \mathrm{erfc}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu_c}{2\max_l\{\gamma_l\}}}\right) \qquad (14)\end{aligned}$$

where $\boldsymbol{\gamma} = [\gamma_1\ \gamma_2\ \dots\ \gamma_L]$ is a vector of the channel gains to the L relays due to Rayleigh fading. In the second line above, the maximization can be moved inside the argument of the complementary error function due to its monoticity.

Assuming the Rayleigh fading is independent on different source-relay links, averaging the conditional IE over the channel gains is simplified by noting that

$$\Gamma = \max_{1\le l\le L}\{\gamma_l\}$$

is the maximum of L i.i.d. exponential random variables, with probability distribution and density functions, respectively, of

$$\begin{aligned}F_\Gamma^{(L)}(\gamma) &= (1-e^{-\gamma})^L; \quad \gamma > 0 \\ f_\Gamma^{(L)}(\gamma) &= Le^{-\gamma}(1-e^{-\gamma})^{(L-1)}; \quad \gamma > 0.\end{aligned}$$

Averaging (14) over Γ

$$\begin{aligned}\mathrm{IE}_{\mathrm{AA,sc}} &= \sqrt{\frac{N}{\pi}}\cos\theta\tau(p)\epsilon \\ &\quad\cdot\int_0^\infty \mathrm{erfc}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu_c}{2\gamma}}\right) f_\Gamma^{(L)}(\gamma)\,d\gamma \\ &= \sqrt{\frac{N}{\pi}}\cos\theta\tau(p)\epsilon \\ &\quad\cdot\int_0^\infty \mathrm{erfc}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu_c}{2\gamma}}\right) Le^{-\gamma}(1-e^{-\gamma})^{(L-1)}\,d\gamma. \qquad (15)\end{aligned}$$

Replacing $(1-e^{-\gamma})^{(L-1)}$ above with its binomial series yields

$$\begin{aligned}\mathrm{IE}_{\mathrm{AA,sc}} &= \sqrt{\frac{N}{\pi}}\cos\theta\tau(p)\epsilon L\sum_{n=0}^{L-1}\binom{L-1}{n}(-1)^n \\ &\quad\cdot\int_0^\infty \mathrm{erfc}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu_c}{2\gamma}}\right) e^{-\gamma(n+1)}\,d\gamma.\end{aligned}$$

Finally, using [18, (6.284)], the average IE with adaptive routing and L relays is

$$\begin{aligned}\mathrm{IE}_{\mathrm{AA,sc}} &= \sqrt{\frac{N}{\pi}}\cos\theta\tau(p)\epsilon\sum_{l=1}^{L}\binom{L}{l}(-1)^{(l-1)} \\ &\quad\cdot\exp\left(-\frac{\beta N p}{\pi}\sqrt{2l\mu_c}\right). \qquad (16)\end{aligned}$$

F. Joint Adaptive Routing and Modulation

Since the CSI-based adaptive routing schemes presume knowledge of the channel gain factors on the source-relay links, a natural extension would be to combine adaptive routing with adaptive modulation. A transmitting node would use knowledge of the relay channel gains and (if available) positions to select the combination of relay and modulation scheme that maximizes the IE of that hop.

The performance analysis above can be extended in straightforward fashion to include adaptive modulation. Let Q be the number of modulation schemes available. Furthermore, let ϵ_q and μ_q be the spectral efficiency and SIR threshold for packet success, respectively, of modulation scheme $q, 1\le q\le Q$, ordered such that $\mu_1 < \mu_2 < \cdots < \mu_Q$. For example, for a rate $1/3$ binary turbo-coded modulation scheme, the SIR thresholds of several 2-D constellations are listed in Table I, along with their spectral efficiencies [19]. These thresholds were obtained from performance curve points corresponding to a frame error rate of 10^{-2}.

To account for adaptive modulation with APA routing, the maximization in (7) is performed over both the relay index l and the modulation index q. The resulting conditional IE for a

TABLE I
SIR CUT-OFF VALUES μ_q AND NORMALIZED CHANNEL GAIN THRESHOLDS $\gamma^*_{\cdot,q} = \gamma_{\cdot,q}/(\beta N p)^2$ BY MODULATION SCHEME

q	Modulation Scheme	ϵ_q	μ_q (dB)	$\gamma^*_{L,q}$	$\gamma^*_{U,q}$
1	QPSK	2/3	−1.1	0	0.1422
2	8-PSK	1	1.7	0.1422	0.2095
3	16-QAM	4/3	3.5	0.2095	0.6058
4	64-QAM	2	7.0	0.6058	1.8729
5	256-QAM	8/3	10.2	1.8729	∞

given transmission with APA routing and adaptive modulation is

$$\mathrm{IE}_{\mathrm{APA,AM}}(\mathbf{r}) = \frac{\tau(p)}{\sqrt{\pi}} \cdot \max_{\substack{1\le l\le L,\\ 1\le q\le Q}} \left\{ \sqrt{N_l}\cos\theta_l \epsilon_q \mathrm{erfc}\left(\frac{\beta N_l p}{\pi}\sqrt{\frac{\mu_q}{2\gamma_l}}\right)\right\}. \quad (17)$$

Similarly, for AA routing and adaptive modulation

$$\mathrm{IE}_{\mathrm{AA,AM}}(\mathbf{r}) = \sqrt{\frac{N_j}{\pi}}\cos\theta_j \tau(p) \cdot \max_q \left\{ \epsilon_q \mathrm{erfc}\left(\frac{\beta N_j p}{\pi}\sqrt{\frac{\mu_q}{2\gamma_j}}\right)\right\}$$

where j is given by (10). The average IE in each case is obtained by averaging over the random vector $\mathbf{r}$.

For the special case of constant $(N, |\theta|)$, the average IE with AA routing and adaptive modulation is obtained by performing the integration in (15), where now the integrand contains a maximization with respect to q

$$\mathrm{IE}_{\mathrm{AA,AM,sc}} = \sqrt{\frac{N}{\pi}}\cos\theta\tau(p) \cdot \int_0^\infty \max_q \left\{ \epsilon_q \mathrm{erfc}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu_q}{2\gamma}}\right)\right\} f_\Gamma^{(L)}(\gamma)\, d\gamma. \quad (18)$$

To evaluate this integral, we note that associated with each modulation scheme is a range of $\gamma, \gamma_{\mathrm{L},q} < \gamma < \gamma_{\mathrm{U},q}$, for which that modulation scheme maximizes the IE [19]. The limits of these ranges, called channel gain thresholds, are such that

$$\epsilon_q \mathrm{erfc}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu_q}{2\gamma}}\right) > \epsilon_{q'} \mathrm{erfc}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu_{q'}}{2\gamma}}\right) \quad \forall\, q' \neq q, \quad \gamma_{\mathrm{L},q} < \gamma < \gamma_{\mathrm{U},q}. \quad (19)$$

Furthermore, because the intervals are contiguous and span the entire range of $0 < \gamma < \infty$, the thresholds satisfy $\gamma_{\mathrm{U},q} = \gamma_{\mathrm{L},q+1}, \gamma_{\mathrm{L},1} = 0$, and $\gamma_{\mathrm{U},Q} = \infty$. Rewriting (18) in terms of these thresholds, we have

$$\mathrm{IE}_{\mathrm{AA,AM,sc}} = \sqrt{\frac{N}{\pi}}\cos\theta\,\tau(p) \cdot \sum_{q=1}^{Q}\int_{\gamma_{\mathrm{L},q}}^{\gamma_{\mathrm{U},q}} \epsilon_q \mathrm{erfc}\left(\frac{\beta N p}{\pi}\sqrt{\frac{\mu_q}{2\gamma}}\right) f_\Gamma^{(L)}(\gamma)\, d\gamma. \quad (20)$$

The channel gain thresholds $\gamma_{\mathrm{L},q}$ and $\gamma_{\mathrm{U},q}$ normalized by $(\beta N p)^2$ are given in Table I for the listed modulation schemes, calculated using (19).

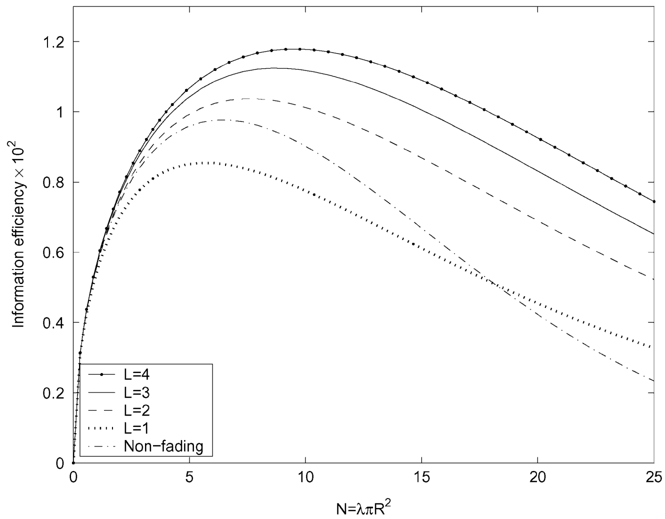

Fig. 5. IE versus transmission range with adaptive routing for special case scenario (constant forward progress and Rayleigh fading), $\theta = 0$, and QPSK modulation.

To summarize, the algorithm for relay and modulation scheme selection with joint APA routing and adaptive modulation is the following.

1) Collect the position (R_l, θ_l) and link gain of each candidate relay.
2) Select the combination of relay and modulation scheme that maximizes the expression in (17).

The algorithm for the simpler joint AA routing and adaptive modulation is the following.

1) Measure the link gain of each candidate relay.
2) Select the relay with the maximum link gain.
3) Select the modulation scheme, q, for which the link gain of the selected relay is bounded by $\gamma_{\mathrm{L},q}$ and $\gamma_{\mathrm{U},q}$.

V. QUANTITATIVE RESULTS

A. *Special Case*

Quantitative results are presented first for the special case of fixed progress and Rayleigh fading. The average IE per hop is evaluated using (16) and (20) and is illustrated as a function of the transmission range in terms of N. Since the factor due to θ is simply a constant scaling factor in the special case, θ in these results is taken to be zero. In each case, asynchronous CDMA with rectangular chips is assumed, the processing gain is 11, and the transmission probability is $p = 0.271$, which was shown in [12] to optimize the expected progress and, in this case, the IE as well (see also [13]).

Fig. 5 illustrates the IE for various orders of route diversity L, and the result for the nonfading channel is shown as well for comparison. The modulation scheme is QPSK in each case. In general, an optimum transmission range exists in each case at which IE is maximized, consistent with previous results [11]–[14]. At lower transmission ranges (smaller N), the gain in throughput is more than offset by the decrease in progress per hop, and *vice versa* at higher transmission ranges. Of particular interest here, though, is the improvement in IE with the number of relay alternatives, L. In fact, the gain with second-order route

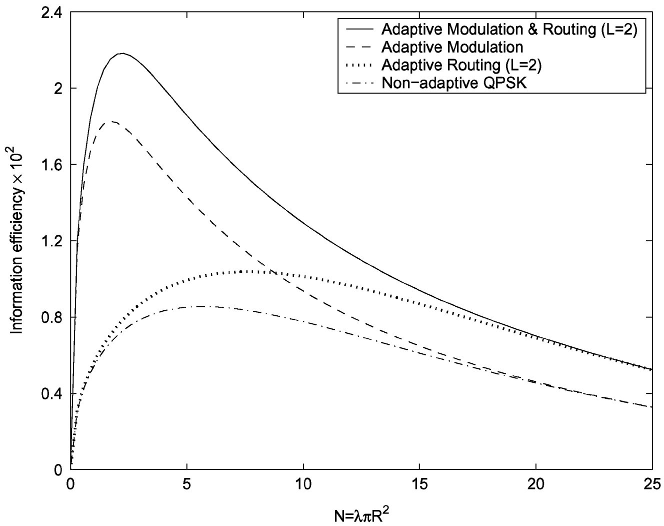

Fig. 6. IE versus transmission range with adaptive routing and adaptive modulation, for special case scenario (constant forward progress and Rayleigh fading), and $\theta = 0$.

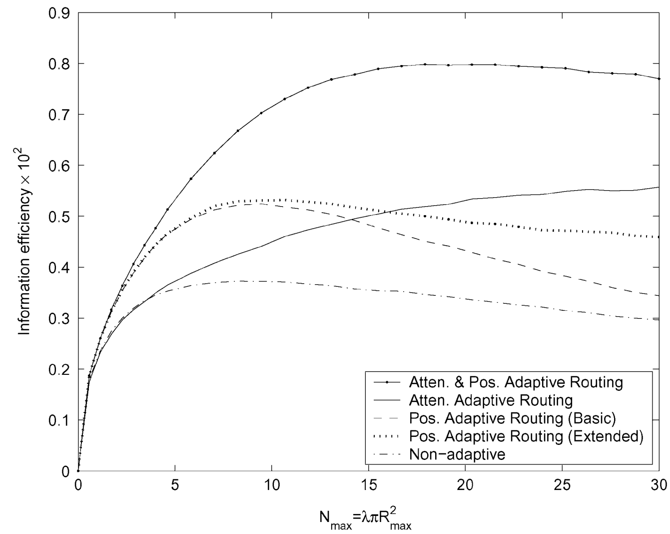

Fig. 7. Monte Carlo results for IE versus transmission range with various adaptive routing schemes, general case, with Rayleigh fading, 8-dB lognormal shadowing, and QPSK modulation.

diversity $(L = 2)$ already more than makes up for the loss due to fading. The additional gains achieved by increasing the route diversity beyond $L = 2$ are diminishing, which is a result that is consistent with diversity gain in general. These results show that a gain over the nonfading channel is available with even limited selectivity in per-hop routing.[3]

Fig. 6 illustrates the relative performance of adaptive routing, adaptive modulation and their combination for the special case scenario. The adaptive modulation results are based on selective use of QPSK, 16-QAM, 64-QAM, and 256-QAM. Adaptive routing, here, is based on second-order route diversity $(L = 2)$. The nonadaptive case using QPSK modulation is shown as well for reference. Adaptive modulation increases the IE, especially at short link distances for which higher order modulation schemes are more likely to be used. Adaptive routing, on the other hand, exploits spatial diversity to improve performance at longer transmission distances. The combination of adaptive routing and adaptive modulation yields more improvement than either adaptive scheme alone over a wide range of transmission distances. The performance of joint adaptive routing and modulation is discussed more fully next for the general case.

B. General Case

Quantitative results are presented here for the general case in which relays are randomly located in the transmission range of the transmitting node, as depicted in Fig. 2. Results are obtained by evaluating the average IE (8) through Monte Carlo simulation of the random variables N_l, θ_l, and $\mathcal{C}_l, 1 \le l \le L$. Furthermore, the number of relay alternatives per hop L is a function of the transmission range and is modeled as follows:

$$L \triangleq \min(L_p, L_{\max})$$

where L_p represents the number of nodes in the half-disc of radius $R_{\max}$, which according to the system model is Poisson distributed with mean $\lambda\pi R_{\max}^2/2 = N_{\max}/2$ and conditioned on the event that at least one relay is present. A maximum value of $L_{\max}$ is imposed as a practical constraint on the number of relay alternatives that a transmitting node can realistically consider. For the results presented next, $L_{\max} = 5$.

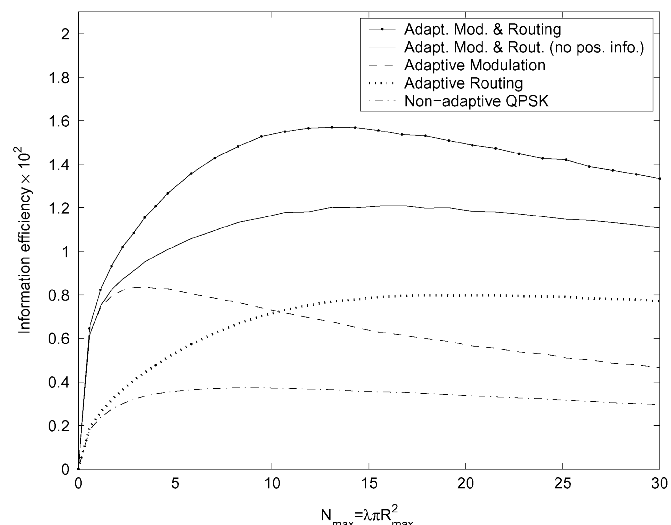

Fig. 8. Monte Carlo results for IE versus transmission range with adaptive routing and adaptive modulation, general case, with Rayleigh fading and 8-dB lognormal shadowing.

The channel gain $\mathcal{C}_l$ is due to a combination of Rayleigh fading and 8-dB lognormal shadowing. The shadowing on different source-relay links is correlated based on their angle-of-arrival difference (AAD). The AAD/distance-dependent cross-correlated shadowing model "1.0/0.0 R6" proposed in [20] is applied here. Results for the average IE are based on 100 000 independent realizations of all the random variables involved. Other system parameters are the same as those used in the previous subsection.

Fig. 7 compares the performance of the various adaptive routing schemes described earlier in terms of average IE versus transmission range $N_{\max}$. APA routing performs best, as ex-

[3]Fading has the dual effect of decreasing both the desired signal strength and the interference, on average. The fading and nonfading IE curves cross at $N = 18$ because the latter effect is dominant for large transmission ranges.

TABLE II
SUMMARY OF ADAPTIVE ROUTING SCHEMES

Adaptive Scheme	Information Required	Remarks	IE Gain
Adaptive Routing Schemes			
Attenuation Adaptivity (AA)	Channel gains on source relay links	Selects closer relays for higher SIR	1.5
Position Adaptivity (PA) – Basic	Positions of relays and final destination	Selects farther relays for greater progress per hop	1.4
Position Adaptivity (PA) – Extended	Positions of relays/final destination; probability of success as a function of distance	Improves performance relative to basic PA (i.e., MFR) at longer transmission ranges	1.4
Atten. & Position Adaptivity (APA)	Channel gains; position information; interference dispersion parameter (for conditional probability of success)	Combines CSI and position information to maximize the *expected* progress per hop	2.1
Joint Adaptive Routing and Modulation Schemes			
AA Routing and Adaptive Modulation	Channel gains; channel gain thresholds	Achieves much of the available gain in info. efficiency with a simpler metric	3.2
APA Routing and Adaptive Modulation	Channel gains; position information; interference dispersion parameter	Combines CSI and position information to maximize the information efficiency per hop	4.2

pected, since both link attenuation and position information are utilized in selecting a relay. The cost of having no knowledge of either the relay positions or the link attenuations is reflected in the lower IE of the attenuation adaptive and the position adaptive schemes, respectively. In each case, the lack of that information results in a performance penalty of 30%–40%. Without position information, attenuation adaptive routing tends to select nearby relays, forgoing the potentially greater progress offered by farther relays. Conversely, without CSI, position adaptive routing tends to select farther relays, ignoring the impact on link throughput of the channel attenuation. At longer transmission ranges, attenuation adaptive routing outperforms position adaptive routing because the former avoids the tendency of the latter to "overreach" and select a relay near the outer limit of the transmission range, regardless of its link quality. The "basic" position adaptive scheme is equivalent to MFR routing. The "extended" version represents an improvement over basic MFR routing by accounting for the impact of distance on link throughput, as described earlier.

Fig. 8 illustrates results with adaptive routing, adaptive modulation, and joint adaptive routing and modulation. The nonadaptive QPSK case is shown as well for reference. Except where noted, the results with adaptive routing are based on the APA scheme. These results lead to several important observations. Adaptive modulation by itself favors shorter transmission ranges because short links permit use of more spectrally efficient constellations. On the other hand, adaptive routing by itself favors longer transmission ranges because, with sufficient diversity, larger progress links with favorable channel conditions can be found. More importantly, the combination of adaptive routing and adaptive modulation balances these two tendencies and results in a significant increase in IE. This improvement is due to the fact that the adaptive routing function selects the best relay in terms of progress and channel state, while the adaptive modulation function maximizes the local throughput on that link. For example, for a transmission range that would include ten neighbors on average, the combination of adaptive routing and modulation more than doubles the IE of either adaptive scheme alone and more than quadruples the efficiency of the nonadaptive scheme.

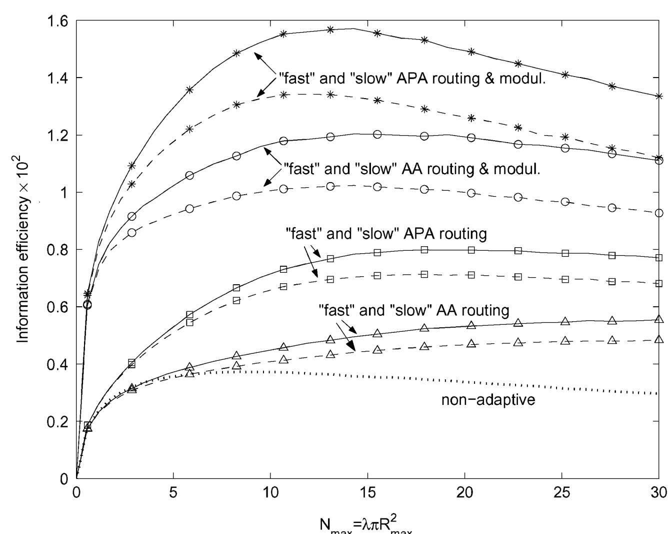

Fig. 9. Comparison of attenuation adaptive schemes with and without adaptivity to the fast fading attenuation; channel with Rayleigh fading and 8-dB lognormal shadowing.

Fig. 8 also includes the result for attenuation adaptive routing and modulation, that is, joint adaptation without knowledge of position information. Although the lack of position information lowers the IE by 25% at $N = 10$, adaptive routing and modulation based on link attenuation alone is still more than three times as efficient as the nonadaptive scheme.

Table II summarizes the adaptive routing and joint adaptive routing and modulation schemes considered above. The table lists the various schemes, their requirements, and their performance characteristics. The last column (IE Gain) is defined as the ratio of the scheme's peak IE to that of nonadaptive QPSK.

The previous results for attenuation adaptivity assume the transmitter has knowledge of the overall link attenuation, that is, the combined effect of path loss, shadowing, and small-scale fading. In some situations, such as fast fading channels, capturing the effect of small-scale fading in the channel measurement may not be feasible, with only the slower effects due to path loss and shadowing being reliably measured. To examine the impact of this more limited measurement of the link attenuation, Fig. 9 compares the performance of attenuation adaptive routing with and without knowledge of the small-scale fading attenuation (referred to in the figure as "fast" and "slow" adaptivity, respectively). Results are shown, as well, for the case of joint adaptive routing and modulation. The lack of knowledge of the fading attenuation results in a 15% penalty in IE when joint adaptive routing and modulation is employed and a 12% penalty when only adaptive routing is employed, irrespective of whether position information is utilized. These results indicate that most of the potential gain from attenuation adaptivity can be achieved with knowledge of only the slowly varying components of the link attenuation, which is consistent with a similar result found in [19].

VI. Summary

Channel-adaptive routing was investigated as a means for exploiting the inherent spatial diversity of multihop networks. Two classes of routing protocols were identified which would readily enable channel adaptivity, namely, position-based routing, and multipath routing, both of which provide a transmitting node with multiple next-hop alternatives with which to forward a packet to the destination. By tracking changes in channel state on these next-hop links, a node could consistently choose that link which presents the best opportunity for transmission at any given time.

Through analytical means for a special case, the impact of increasing orders of route diversity was evaluated, and a simple second-order route diversity scheme was found to more than compensate for the loss due to Rayleigh fading. This result implies that low complexity multipath routing schemes (i.e., with limited next-hop selectivity) can effectively negate the loss in efficiency due to Rayleigh fading and even exploit it. Through numerical means for a more general case, three varieties of adaptive routing were compared, depending on whether position information, link attenuation or both are available in the routing decision. The penalty of lacking either of these elements of information is a 30%–40% decrease in performance. The relative gains of adaptive routing, adaptive modulation, and their combination were also considered. While either adaptive scheme alone results in a doubling of IE relative to a nonadaptive scheme, the combination of the two adaptive techniques more than quadruples efficiency. Even without position information, attenuation-adaptive routing and modulation more than triples IE. This result suggests a significant potential for increasing system capacity in multihop packet radio networks through adaptive routing, which selects a link with favorable channel conditions, combined with adaptive modulation, which maximizes the throughput on that link. Current work aims to evaluate per-hop channel-adaptive routing protocols in a network simulation environment in terms of end-to-end throughput, delay, and network stability.

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