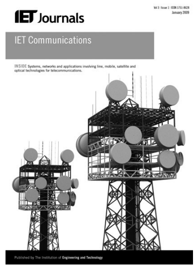
www.ietdl.org

Published in IET Communications
Received on 15th June 2011
Revised on 18th January 2012
doi: 10.1049/iet-com.2011.0457



ISSN 1751-8628

Diversity of multi-hop cluster-based routing with arbitrary relay selection

Q. Deng A.G. Klein

Department of Electrical and Computer Engineering, Worcester Polytechnic Institute, 100 Institute Rd, Worcester MA 01609, USA
E-mail: qxdeng@wpi.edu

Abstract: Clustered multi-hop wireless networks have attracted significant attention for their robustness to fading, hierarchical structure, and ability to exploit the broadcast nature of the wireless channel. The authors propose an opportunistic routing (or relay selection) algorithm for such networks. In contrast to the majority of existing approaches to routing in clustered networks, the algorithm presented in this study only requires channel state information in the final hop, which is shown to be crucial for reaping the diversity offered by the channel. In addition to exploiting the available diversity, our simple cross-layer algorithm has the flexibility to simultaneously satisfy an additional routing objective such as the maximisation of network lifetime. The authors demonstrate through analysis and simulation that our proposed routing algorithm attains full diversity under certain conditions on the cluster sizes, and its diversity is equal to the diversity of more complicated approaches that require full channel state information.

1 Introduction

The use of cooperative communication in wireless multi-hop networks has attracted much interest in recent years for its promise of robustness against fading, increased data rates and improved energy efficiency, among other benefits. To provide scalable routing, meet quality-of-service requirements and ease mobility management in multi-hop networks with a large number of mobile nodes, a hierarchical structure based on clustering has been considered since the early days of mobile packet radio [1]. Indeed, a wide range of algorithms exist for grouping the nodes into clusters based on some criteria, such as proximity or movement patterns [2, 3].

Routing algorithms for multi-hop systems [4, 5] have also been studied extensively, with the goal of optimising various objectives. For example, at the higher network layers, routing algorithms have been proposed to maximise network lifetime [6] or minimise total power [7]. Recognising that the issues of routing and exploiting cooperative diversity are inherently linked, routing algorithms using cross-layer design have also been proposed (see, for example [8]). For this latter class of algorithms, one of the major concerns is in developing routing algorithms that attain 'full diversity'.

Although a number of studies on the diversity attained by various multi-hop routing algorithms have been conducted [9, 10], less attention has been devoted to the diversity of routing algorithms in 'clustered' multi-hop networks [11]. One notable exception is [12] where several routing algorithms were proposed. In that work, an optimal routing algorithm was first considered, which assumes availability of global instantaneous channel state information (CSI), and performs a search over all possible routes at a central controller. Subsequently, a more practical routing algorithm called *ad hoc* routing (AHR) was proposed, which generates routes in a hop-by-hop manner, always routing the next hop through the node with the largest channel gain. Although AHR does not require global CSI, it does require CSI between clusters so that each transmitting node can choose the best route. If all clusters in the multi-hop network have K nodes, both the optimal routing and AHR approaches were shown to yield a full diversity order of K, although the power gain of AHR was inferior to optimal approach.

Another related work which considers routing protocols and diversity in clustered multi-hop networks is [13]. The protocol used in [13] requires two phases: one for intra-cluster communication and another for inter-cluster communication. Then, multiple relays in each cluster transmit simultaneously to the next cluster using CDMA with RAKE receivers, although the end-to-end diversity is not explicitly computed. Finally, in [14] the AHR protocol of [12] is modified by using an additional relay in each hop; this results in a performance improvement at the expense of an increase in complexity. However, all of these protocols [12–14] require instantaneous CSI at each transmitting node, and some of them even require full global CSI.

Here, we propose a simple opportunistic routing strategy which only requires CSI in the last hop, and selects an arbitrary node in the cluster to perform forwarding in all other hops. Quite remarkably, we show that this simple scheme can achieve full diversity while exhibiting performance equal to the AHR approach. Furthermore, owing to the flexibility in node selection in the intermediate hops, our scheme can also be adapted to optimise an external routing objective. By performing opportunistic routing – as opposed to pre-selecting a specific destination node in the next cluster before transmission – our scheme results in a significant complexity reduction and drastically reduced requirements on knowledge of CSI when compared with the existing routing protocols for clustered multi-hop networks [12–14]. Several works have investigated opportunistic routing at the higher network layers, for example [15, 16], although these works have not analysed the attainable diversity.

2 System model

We consider a wireless multi-hop network as illustrated in Fig. 1, where the wireless communication system consists of three kinds of nodes: a source node (**S**), clustered relay nodes and a destination node (**D**). All nodes are assumed to be equipped with a single antenna, and we assume the relays operate in half-duplex mode so that they do not transmit and receive at the same time. Furthermore, we assume each relay node uses the decode-and-forward protocol and uses repetition coding. Only relays which correctly decode the message from the previous hop can participate in forwarding the decoded message in the next hop. We define such relays as ‘decoding relays’ and they form a ‘decoding set’. In practice, the decision of whether the message is decoded successfully can be made with the help of a checksum (e.g. CRC) and we assume that relays which pass this checksum have decoded the message error-free. To avoid interference, we consider time division multiple access in the medium access control layer, which allows each cluster to transmit its information in orthogonal time-domain subchannels.

We assume that the distance between relay clusters is much larger than that between nodes in any one cluster, so the point-to-point channels between two clusters are assumed to have i.i.d. Rayleigh fading statistics [17], and each channel coefficient is modelled as a complex Gaussian random variable with zero mean. Relay clusters are assumed to be spaced sufficiently far apart so that relays in a given cluster can only communicate with the neighbouring cluster. Relaxation of this condition would permit combining multiple received copies at each hop, but would lead to overly optimistic results because of the high signal-to-noise ratio (SNR) analysis we employ. We note that the routing algorithm proposed in Section 3 can be readily extended to combine signals from multiple clusters, and this would of course improve performance.

We denote the number of total hops from the source to the destination as M. The $M-1$ relay clusters are located between the source and the destination. The relay cluster which receives in the mth hop is denoted as $\mathcal{R}_m$ and contains K_m relays for $1 \leq m \leq M-1$. Each node in $\mathcal{R}_m$ is denoted as $\boldsymbol{R}_{j,m}$ where j denotes its index in the cluster and $1 \leq j \leq K_m$. The decoding relays that can correctly decode the message from the mth hop consist of the decoding set $\mathcal{D}_m$ whose size is denoted as $|\mathcal{D}_m|$. In the subscript, we denote s as the source node **S**, d as the destination **D** and $r_{i,m}$ as the ith relay in the relay cluster $\mathcal{R}_m$. The channels gains in the first hop are denoted as $h_{sr_{j,1}}$ with variance λ_1 where $1 \leq j \leq K_1$, the gains in the mth $(2 \leq m \leq M-1)$ hops as $h_{r_{j,m-1}r_{k,m}}$ with variance λ_m where $1 \leq j \leq K_{m-1}$ and $1 \leq k \leq K_m$ and the gains at the last hop as $h_{r_{j,M-1}d}$ with variance λ_M where $1 \leq j \leq K_{M-1}$. We note that our system model is nearly identical to the one considered in [12], although our model is more general as each cluster can have different numbers of relays K_m. As in [12–14], we assume that cluster-level routing tables have been predetermined, and we focus on relay selection within each cluster.

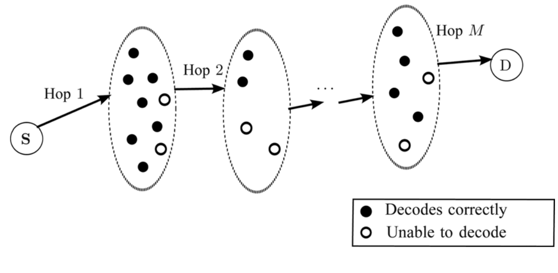


Fig. 1 *System model showing an example decoding set*

To simplify the analysis, we assume that there is no power control and all nodes have the same average power constraint P watts and transmission bandwidth W hertz. In addition, all links have additive noise which is assumed to be mutually independent, zero-mean circularly symmetric complex Gaussian with variance N_0 and the discrete-time SNR is defined as

$$\mathrm{SNR} \triangleq \frac{P}{WN_0}.$$

We choose to treat the case of equal node powers and equal noise variances for simplicity; in the high SNR regime we are considering, the use of unequal powers would not change the final diversity result, although it would alter the power gain. Although our model assumes all channels in the ith hop have equal variance λ_i, we note that even without the identical distribution assumption at each hop, the resulting diversity is the same. The diversity analysis below focuses on the SNR exponent of the outage probability which is unaffected by relative node powers.

3 Best-last arbitrary-rest multi-hop relaying

In this section, we propose a relaying algorithm called Best-Last Arbitrary-Rest (BLAR) which arbitrarily selects a single relay within the decoding set for the first $M-1$ hops, and then selects the best relay within the decoding set for the last hop. More sophisticated relay selection is required in the last hop; otherwise, the last hop would become a bottleneck with diversity order of 1 since there is only one antenna at the destination and spatial diversity could not be achieved. We note that arbitrary relay selection over the decoding set can be done deterministically, or randomly according to any prescribed probability mass function (PMF). For example, it can be uniformly distributed so that the relays are selected with equal probability, or it can be designed to optimise some performance objective. If the minimum latency route is desired, the decoding relay which is the first that occupies the channel to the next-hop cluster can be the actual forwarding relay with probability 1; or if we want to maximise network lifetime, the decoding relay with the largest available battery energy should be the forwarding relay. This method has the advantage that no channel state information at the transmitter (CSIT) is needed for the first $M-1$ hops, and only partial CSIT is

doi: 10.1049/iet-com.2011.0457

needed for the final hop. In addition, we note that there is no intra-cluster communication required for this protocol.

At the first hop, after the source broadcasts the message, all the relays in the first relay cluster $\mathcal{R}_1$ try to decode the message. The relays which can decode the message correctly form the decoding set $\mathcal{D}_1$. Each decoding relay in $\mathcal{D}_1$ takes the forwarding responsibility with probability predefined by the system as previously explained. For uniformly distributed random relay selection, each decoding relay in $\mathcal{D}_1$ waits for a random time which is uniformly distributed within a range with predefined maximum time, and the first to transmit becomes the chosen relay. For objective optimising relay selection, the relay that optimises the objective function within the decoding set waits for the minimal time and will be the first in the decoding set to send the decoded signal. At the next hop, the chosen relay works as the source in the first hop and the same random relaying procedure continues in the decoding set $\mathcal{D}_2$ up until $(M-1)$th hop.

In the last hop, the best relay is selected within $\mathcal{D}_{M-1}$, where the 'best' relay is defined as the one with the largest channel amplitude from the relay in $\mathcal{D}_{M-1}$ to destination. The best relay selection process can be completed either centrally at the destination or in a distributed manner by relays, as follows:

- *Centralised selection*: As each decoding relay $\mathcal{D}_{M-1}$ is aware that it has the direct link to the destination, in turn, each decoding relay transmits some known information to the destination, and the destination estimates each relay-to-destination channel. The destination chooses the relay with the largest relay-to-destination channel amplitude, and feeds back this information to the relays. The feedback requires $|\mathcal{D}_{M-1}|$ bits, and is assumed to be fed back reliably.
- *Distributed selection:* At the final hop, the relay–destination channel and the destination–relay channel are assumed to be the same because of reciprocity. For some decoding relay in $\mathcal{D}_{M-1}$ that knows it has the direct link to the destination, it transmits a message indicating training needed to the destination. On receiving that information, the destination broadcasts training data, where each relay in $\mathcal{D}_{M-1}$ individually estimates its channel to the destination. Each relay in $\mathcal{D}_{M-1}$ waits for a time duration which is inversely proportional to its relay–destination channel amplitude before forwarding its decoded signal [18], so the relay with the largest channel amplitude will be the first to send the decoded signal to the destination. Before its actual transmission, the selected relay will first broadcast a flag message. Other decoding relays do not start transmission if they overhear the flag signal from the best relay. This flag signal is assumed known and can be detected without error.

We note that distributed selection in the last hop can yield smaller overhead and delay as the overhead of performing distributed selection is negligible compared with the training required for centralised selection. We also note that it is possible for the decoding set in any hop to be empty; in this case, the relaying procedure stops and the message cannot be transmitted to the destination successfully.

4 Outage analysis

In this section, we analyse the outage probability of the BLAR algorithm proposed in the previous section. The outage probability is defined as the probability that the mutual information I between source and destination falls below a certain rate R, and is denoted $\Pr[I < R]$. In multi-hop relaying, the outage event can be caused by an outage at any intermediate hop (i.e. if $|\mathcal{D}_m| = 0$ for some m). Thus, the outage event can be expressed as the union of the following three disjoint events

$$\begin{aligned}\{I < R\} = &\{I < R \cap |\mathcal{D}_1| = 0\} \\ &\bigcup \cup_{m=2}^{M-1} \{I < R \cap |\mathcal{D}_m| = 0 \cap_{1\le i<m} \{|\mathcal{D}_i| \neq 0\}\} \\ &\bigcup \{I < R \cap_{1\le i\le M-1} \{|\mathcal{D}_i| \neq 0\}\}\end{aligned}$$

which correspond to conditioning on unsuccessful decoding in the first, intermediate (i.e. the mth), and final hops, respectively. As the outage probability conditioned on any empty decoding set is 1, we further have

$$\begin{aligned}\Pr[I < R \cap |\mathcal{D}_1| = 0] &= \Pr[I < R|\, |\mathcal{D}_1| = 0] \Pr[|\mathcal{D}_1| = 0] \\ &= \Pr[|\mathcal{D}_1| = 0]\end{aligned}$$

and similarly

$$\begin{aligned}\Pr[I < R \cap\ |\mathcal{D}_m| = 0 \cap_{1\le i<m} \{|\mathcal{D}_i| \neq 0\}] \\ = \Pr[|\mathcal{D}_m| = 0 \cap_{1\le i<m} \{|\mathcal{D}_i| \neq 0\}].\end{aligned}$$

Thus, the outage probability can be written as

$$\begin{aligned}P_{\text{out}} = &\Pr[|\mathcal{D}_1| = 0] \\ &+ \sum_{m=2}^{M-1} \Pr[|\mathcal{D}_m| = 0 \cap_{1\le i<m} \{|\mathcal{D}_i| \neq 0\}] \\ &+ \Pr[I < R \cap_{1\le i\le M-1} \{|\mathcal{D}_i| \neq 0\}] \qquad (1)\end{aligned}$$

where the second term in (1) denotes the probability that the decoding set after mth hop is empty with non-empty previous decoding sets through the route, the third term denotes the outage probability at the last hop with non-empty previous decoding sets through the route. We next analyse the probability of the three events in (1) one by one.

As mentioned above, we will derive the diversity order by investigating the outage behaviour in the high SNR regime. Toward that end, we use the notation $\doteq$ to denote asymptotic equality in the large SNR limit with $A \doteq B$ meaning

$$\lim_{\text{SNR}\to\infty} \frac{\log A}{\log \text{SNR}} = \lim_{\text{SNR}\to\infty} \frac{\log B}{\log \text{SNR}}.$$

4.1 Probability of an empty decoding set after the first hop

The first term in (1) corresponds to the probability of having an empty decoding set after the first hop. The mutual information between source and jth relay in $\mathcal{R}_1$ at the first hop is

$$I_{sr_{j,1}} = \log(1 + |h_{sr_{j,1}}|^2 \text{SNR})$$

where $1 \le j \le K_1$. To calculate the probability of a given

doi: 10.1049/iet-com.2011.0457

decoding set $\Pr[\mathcal{D}_1]$, first let

$$b \triangleq \frac{2^R - 1}{\mathrm{SNR}}.$$

The probability that ith relay node is in $\mathcal{D}_1$ is

$$\begin{aligned}\Pr[\boldsymbol{R}_{j,1} \in \mathcal{D}_1] &= \Pr[I_{sr_{j,1}} > R] \\ &= \Pr[|h_{sr_{j,1}}|^2 > b] \\ &= \int_b^{+\infty} \lambda_1 \mathrm{e}^{-\lambda_1 x}\,\mathrm{d}x \\ &= \mathrm{e}^{-\lambda_1 b}.\end{aligned}$$

As each relay independently decodes the message, and as the channels from source to each relay in $\mathcal{R}_1$ are independent, the probability of a particular decoding set is

$$\begin{aligned}\Pr[\mathcal{D}_1] &= \prod_{\boldsymbol{R}_{i,1} \notin \mathcal{D}_1} (1 - \mathrm{e}^{-\lambda_1 b}) \prod_{\boldsymbol{R}_{i,1} \in \mathcal{D}_1} \mathrm{e}^{-\lambda_1 b} \\ &\doteq (\lambda_1 b)^{K_1 - |\mathcal{D}_1|} \qquad (2)\end{aligned}$$

where (2) follows when SNR is high, $\mathrm{e}^{-\lambda_1 b} \doteq 1$ and $1 - \mathrm{e}^{-\lambda_1 b} \doteq \lambda_1 b$; as such, only terms of b with the smallest exponent in the polynomial are kept. Thus, we have

$$\Pr[|\mathcal{D}_1| = 0] \doteq (\lambda_1 b)^{K_1}. \qquad (3)$$

4.2 Probability of an empty decoding set in intermediate hops

We first analyse the probability of an empty decoding set after the second hop, and then generalise the argument to subsequent hops up to before the final hop. Given a non-empty decoding set $\mathcal{D}_1$, let $p_{j,i}$ be the chosen PMF for random selection after the ith hop for the jth relay in the decoding set. Thus, after the first hop, the distribution for random relay selection is $p_{1,1}, p_{2,1}, \ldots, p_{|\mathcal{D}_1|,1}$, and the probability of a specific decoding set after the second hop conditioned on $\mathcal{D}_1$ is

$$\Pr[\mathcal{D}_2 | \{\mathcal{D}_1 \cap |\mathcal{D}_1| \neq 0\}] = \sum_{\boldsymbol{R}_{j,1} \in \mathcal{D}_1} p_{j,1} \Pr[\mathcal{D}_2 | \boldsymbol{R}_{j,1}] \qquad (4)$$

where $\Pr[\mathcal{D}_2 | \boldsymbol{R}_{j,1}]$ denotes the probability of $\mathcal{D}_2$ given the forwarding relay is $\boldsymbol{R}_{j,1}$. With the i.i.d. assumption for each fading coefficient in the second hop, for any $\boldsymbol{R}_{j,1} \in \mathcal{D}_1$, a similar argument as for the decoding set of $\mathcal{D}_1$ gives

$$\Pr[\mathcal{D}_2 | \boldsymbol{R}_{j,1}] \doteq (\lambda_2 b)^{K_2 - |\mathcal{D}_2|} \qquad (5)$$

Substituting (5) into (4), we have

$$\Pr[\mathcal{D}_2 | \{\mathcal{D}_1 \cap |\mathcal{D}_1| \neq 0\}] \doteq (\lambda_2 b)^{K_2 - |\mathcal{D}_2|}$$

Applying the total probability theorem, we have

$$\begin{aligned}\Pr[\mathcal{D}_2 \cap |\mathcal{D}_1| \neq 0] &= \sum_{|\mathcal{D}_1| \neq 0} \Pr[\mathcal{D}_2 | \mathcal{D}_1] \Pr[\mathcal{D}_1] \\ &\doteq (\lambda_2 b)^{K_2 - |\mathcal{D}_2|} \sum_{|\mathcal{D}_1| \neq 0} \Pr[\mathcal{D}_1] \\ &= (\lambda_2 b)^{K_2 - |\mathcal{D}_2|} (1 - P[|\mathcal{D}_1| = 0]) \qquad (6) \\ &\doteq (\lambda_2 b)^{K_2 - |\mathcal{D}_2|} (1 - (\lambda_1 b)^{K_1}) \\ &\doteq (\lambda_2 b)^{K_2 - |\mathcal{D}_2|} \qquad (7)\end{aligned}$$

where the summation in (6) is over all possible decoding sets whose cardinality is non-zero at the first hop. We see from (7) that as long as $\mathcal{D}_1$ is not empty, with the random selection, the probability of the decoding set after the second hop is not affected by the decoding set at the first hop. This makes intuitive sense because no matter which decoding relay is selected, the total number of fading links in the next hop only depends on the number of receiving relays K_2 in the second cluster, and the probability of $|\mathcal{D}_2|$ only depends on the links which are in deep fade. We next generalise the results to $2 < m \leq M - 1$. Once the relay is selected, the probability of the decoding set in the next hop does not depend on the selected relay or the decoding sets in the previous hops. Hence, we can conclude that

$$\begin{aligned}\Pr[\mathcal{D}_m \cap_{1 \leq i < m} \{|\mathcal{D}_i| \neq 0\}] &= \Pr[\mathcal{D}_m \cap |\mathcal{D}_{m-1}| \neq 0] \\ &\doteq (\lambda_m b)^{K_m - |\mathcal{D}_m|} \qquad (8)\end{aligned}$$

where (8) follows very similar steps as (6) to (7). Correspondingly, the probability of an empty decoding set at the mth hop is

$$\Pr[|\mathcal{D}_m| = 0 \cap_{1 \leq i < m} \{|\mathcal{D}_i| \neq 0\}] \doteq (\lambda_m b)^{K_m}. \qquad (9)$$

4.3 Outage probability at destination

If one of the decoding sets $\mathcal{D}_{1,\ldots,M-1}$ is empty, the outage probability is 1 as there is no path for the message to flow to the destination. Conditioning on non-empty sets for the first $M-1$ hops, and assuming that the destination selects the relay with the largest instant channel gain at the last hop, the conditional outage probability for the last hop is

$$\begin{aligned}&\Pr[I < R | \cap_{1 \leq i \leq M-1} \mathcal{D}_i \cap_{1 \leq i \leq M-1} \{|\mathcal{D}_i| \neq 0\}] \\ &\quad = \Pr[\log(1 + \max_{\mathrm{R}_{j,M-1} \in \mathcal{D}_{M-1}} |h_{r_{j,M-1}d}|^2 \mathrm{SNR}) < R] \\ &\quad = \Pr[\max_{\mathrm{R}_{j,M-1} \in \mathcal{D}_{M-1}} |h_{r_{j,M-1}d}|^2 < b] \\ &\quad = \prod_{\mathrm{R}_{j,M-1} \in \mathcal{D}_{M-1}} \Pr[|h_{r_{j,M-1}d}|^2 < b] \\ &\quad \doteq (\lambda_M b)^{|\mathcal{D}_{M-1}|}. \qquad (10)\end{aligned}$$

IET Commun., pp. 1–7
doi: 10.1049/iet-com.2011.0457

Thus, we have

$$\begin{aligned}
\Pr[I < R \cap_{1\le i\le M-1} \{|\mathcal{D}_i| \neq 0\}] \\
&= \sum \Pr[I < R|\mathcal{D}_1, \ldots, \mathcal{D}_{M-1}]\Pr[\mathcal{D}_1, \ldots, \mathcal{D}_{M-1}] && (11)\\
&\doteq \sum (\lambda_M b)^{|\mathcal{D}_{M-1}|} \prod_{m=1}^{M-1} (b\lambda_m)^{K_m-|\mathcal{D}_m|} && (12)\\
&= \sum (\lambda_M b)^{|\mathcal{D}_{M-1}|}(b\lambda_{M-1})^{K_{M-1}-|\mathcal{D}_{M-1}|} \prod_{m=1}^{M-2} (b\lambda_m)^{K_m-|\mathcal{D}_m|} && (13)\\
&\doteq \left[(\lambda_M + \lambda_{M-1})^{K_{M-1}} - \lambda_{M-1}^{K_{M-1}}\right] b^{K_{M-1}} && (14)
\end{aligned}$$

where the summations in (11)–(13) are over all possible combinations of non-empty decoding sets from the first hop to the $(M-1)$th hop, that is, the set where $\cap_{1\le i\le M-1}\{|\mathcal{D}_i| \neq 0\}$. Equation (14) comes from the fact that the summation is dominated by the terms where b has the smallest exponent, which occurs when $|\mathcal{D}_m| = K_m$ for $1 \le m < M-1$.

4.4 End-to-end outage and comparison

Substituting (3), (9) and (14) into (1), the total outage probability is

$$\begin{aligned}
P_{\text{out}} &\doteq \sum_{m=1}^{M-2} (\lambda_m b)^{K_m} + (\lambda_{M-1} + \lambda_M)^{K_{M-1}} b^{K_{M-1}} \\
&\doteq b^{d_{\text{BLAR}}} \sum_{m:K_m=d_{\text{BLAR}}} \beta_m^{d_{\text{BLAR}}}
\end{aligned} \quad (15)$$

where we denote $\beta_m \triangleq \lambda_m$, $\beta_{M-1} \triangleq \lambda_M + \lambda_{M-1}$, the summation in (15) is over all the hops that have the smallest number of relays in the cluster, and

$$d_{\text{BLAR}} \triangleq \min_{m=1,\ldots,M-1} K_m. \quad (16)$$

From (16), the achievable diversity order (i.e. the SNR exponent) is bottlenecked by the minimum number of available relays over all relay clusters. Comparing (15) with (9), the major outage event is the empty decoding set at hops where the number of available receiving relays is the minimum over all relay clusters.

In the case where all clusters have the same number of nodes, that is, $K_m = K$ for all $1 \le m \le M-1$, we have

$$P_{\text{out}} \doteq \left(\sum_{m=1}^{M-2} \lambda_m^K + (\lambda_{M-1} + \lambda_M)^K\right) b^K \quad (17)$$

Comparing (17) with the result in [12; (20), (21)], we see that our algorithm can achieve outage performance identical to AHR in the high SNR regime, even though we arbitrarily choose the forwarding relays for the first $M-1$ hops. The flexibility of being able to arbitrarily select any relay in the decoding set for the first $M-1$ hops allows us to additionally optimise an external routing objective, if desired. The AHR approach [12] does not permit such flexibility as it always chooses the decoding relay which has the best channel gain. In this case, our proposed method and the AHR approach attain the same diversity order and power gain. However, for the optimal routing, the result in [12; (13)] can be further written as $(\lambda_1^K + \lambda_M^K)b^K$ by using the asymptotic equality. Hence, the optimal routing has a power gain of is

$$10\left(\log_{10} \frac{\sum_{m=1}^{M-2} \lambda_m^K + (\lambda_{M-1} + \lambda_M)^K}{\lambda_1^K + \lambda_M^K}\right)\text{dB}$$

over the AHR approach and our proposed scheme in the high SNR regime.

In other works that have investigated diversity in cluster-based multi-hop networks [12–14], the term ‘full diversity’ is often used to describe a routing method that attains a diversity order equal to K, that is, the number of nodes in all clusters. When the number of nodes in each cluster differs, however, the notion of full diversity is quite different. To explore this effect, let us reconsider our cluster-based model with the optimal routing algorithm that uses global CSI in a central controller to preselect the best route [12]. Using the cut-set bound, the outage of any multi-hop routing scheme can be lower bounded by

$$P_{\text{out}}^{\text{opt}} \dot{\ge} \text{SNR}^{-\min_{0\le m\le M-1} K_m K_{m+1}} \quad (18)$$

where by definition $K_0 = K_M = 1$ [19]. In contrast, when performing optimal routing to select the path with the best worst-case link, there are at least $\min_{0\le m\le M-1} K_m K_{m+1}$ distinct bottleneck links in $\prod_{i=1,\ldots,M-1} K_i$ possible paths from source to relay. From equation [12, Lemma 2], the outage of optimal routing with different cluster sizes can be upper bounded by

$$P_{\text{out}}^{\text{opt}} \dot{\le} \text{SNR}^{-\min_{0\le m\le M-1} K_m K_{m+1}}. \quad (19)$$

Combining (18) and (19), we see that optimal routing can attain the maximum possible diversity order given by the cut-set bound and

$$d_{\text{full}} \triangleq \min_{0\le m\le M-1} K_m K_{m+1}. \quad (20)$$

Although the authors in [12] claim that AHR attains full diversity, it can be shown that the AHR approach attains diversity order d_{BLAR}. This is further confirmed in the simulations that follow. The expressions in (16) and (20) show that the diversity order of BLAR is dominated by the diversity order of optimal routing, although we note that $d_{\text{BLAR}} = d_{\text{full}}$ in a wide variety of practical situations. For example, the BLAR and AHR schemes attain full diversity for any multi-hop system with fewer than four hops, which would result in full diversity $\min(K_1, K_2)$ for three hops and K_1 for two hops, as well as systems with a relatively even number of relays in each cluster.

5 Numerical results

We now present numerical performance results to validate the analysis in Section 4. In Table 1, seven simulation scenarios are listed where the d_{BLAR} column shows the achievable diversity by the BLAR and AHR methods, whereas the d_{full} column shows the full diversity achievable by optimal routing.

The curves in Fig. 2 show the outage performance of the three routing methods in scenarios 1 through 3. For BLAR routing, we use a random approach for the arbitrary

Table 1 Simulation scenarios

Scenario	Hops (M)	Nodes per cluster	d_{BLAR}	d_{full}
1	6	$K_1 = 5$, $K_2 = 3$, $K_3 = K_4 = 2$, $K_5 = 6$	2	4
2	10	$K_i = 3$, $1 \le i \le 9$	3	3
3	4	$K_i = 3$, $1 \le i \le 3$	3	3
4	3	$K_1 = K_2 = 3$	3	3
5	4	$K_1 = 3$, $K_2 = 2$, $K_3 = 3$	2	3
6	3	$K_1 = 2$, $K_2 = 3$	2	2
7	4	$K_1 = 8$, $K_2 = 6$, $K_3 = 8$	6	8

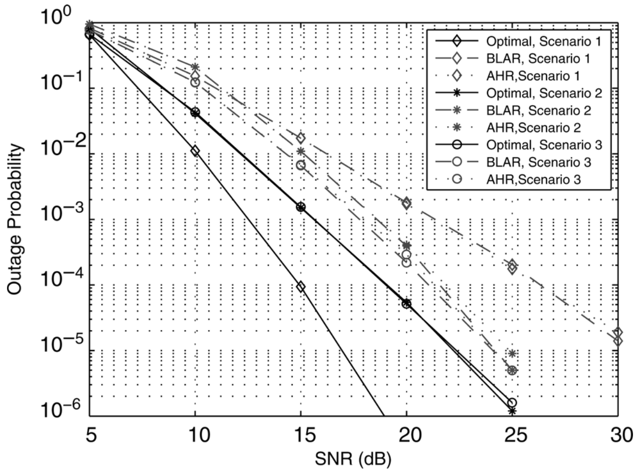


Fig. 2 *Outage comparison of optimal routing, BLAR and AHR, $R = 2$ bits/s/Hz, and $\lambda_{rm} = 1$ for all $1 \le m \le M$*

selection where all decoding nodes are equally likely to be selected. The diversity is represented by the negative slope of outage probability curve in Fig. 2. As expected, optimal routing has a larger diversity than the other two methods in scenario 1 whereas in scenarios 2 and 3 the three methods have the same diversity. The outage performance of AHR and BLAR routing are almost the same for all scenarios 1 through 3. This agrees with our analysis that relay selection without channel knowledge in all but the last hop does not affect the achievable diversity. Thus, with no diversity penalty, the proposed BLAR algorithm offers the flexibility of incorporating an additional routing objective in the first $M-1$ hops.

We next consider the last three scenarios listed in Table 1 to show that the arbitrary relay selection in the first $M-1$ hops does not affect outage performance. The curves in Fig. 3 show the outage performance of BLAR algorithm with three implementations for arbitrary relay selection. The first implementation is to select one of the decoding relays with uniform distribution in the first $M-1$ hops. The second implementation is to maximise the network lifetime. As only one source–destination pair is considered in this study, even use of each relay in the first $M - 1$ clusters will help achieve this objective [20]. Thus, we assume each relay in the first $M-1$ clusters has a counter to record the times that it has forwarded for the source–destination transmission. In each cluster, the decoding relay with the smallest counter number will be the actual forwarding relay. The third implementation is to minimise the routing latency where each decoding relay in the first $M - 1$ clusters waits for a random duration uniformly distributed between 0 and the maximum waiting time and the one waiting for the least time in each cluster is chosen as the actual forwarding relay. Both the second and third relay selection implementations result in outage performance that is almost the same as the one with a uniform distribution, which shows that arbitrary relay selection in the first $M-1$ hops does not affect the diversity.

We use scenario 7 as an example of high diversity order and to study the effect on outage probability of the distance between clusters. In this case, we assume that the distance between the source and the destination equals four unit lengths and the relay clusters are located along the line between the source and the destination. The numerical examples for the distance between clusters are shown in Table 2 where d_m is the distance between the $m-1$th cluster and its next cluster and the mean channel strength is determined as $\lambda_m = d_m^{-3}$. We first focus on the outage performance where $\lambda_m = 1$ for all $1 \le m \le 4$, which is shown in Fig. 4 for $R = 2$ bit/s/Hz and in Fig. 5 for $R = 4$ bit/s/Hz with the legend 'Example 1'. Both outage performances are very similar, except that there exists a power gain about 7 dB for $R = 2$ bit/s/Hz over $R = 4$ bit/s/Hz. At finite SNR regime, with increased number of relays in each cluster, the full diversity does not show up and the diversity benefit of the optimal routing over the AHR and BLAR routing is diminishing. We next study the effect on outage probability of the distance between clusters. For the AHR and BLAR routing, even placement of clusters (example 1) results in a power gain when compared with uneven placement of clusters (examples 2 and 3). However, for optimal routing, the effect of uneven placement of clusters is more complicated. As shown in [12, (13)], the power gain of the optimal routing is only closely related to λ_1 and λ_M where $M = 4$ in this case. Compared with example 1, the larger distance in the first hop and the last hop in example 3 results in a lower power gain of the optimal routing. As example 2 has a shorter distance in the

Table 2 Cluster distance examples for simulation scenario 7 with four hops

Example	Distance
1	$d_1 = d_2 = d_3 = d_4 = 1$
2	$d_1 = d_4 = 0.5$, $d_2 = d_3 = 1.5$
3	$d_1 = d_4 = 1.5$, $d_2 = d_3 = 0.5$

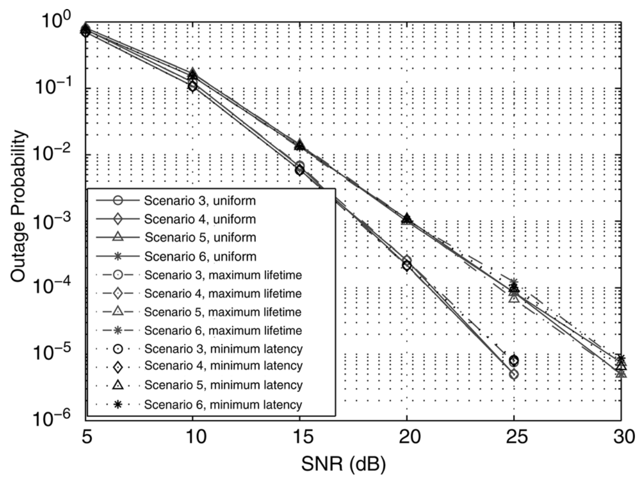


Fig. 3 *Outage comparison of three implementations for arbitrary relay selection, $R = 2$ bits/s/Hz and $\lambda_{rm} = 1$ for all $1 \le m \le M$*

IET Commun., pp. 1–7
doi: 10.1049/iet-com.2011.0457

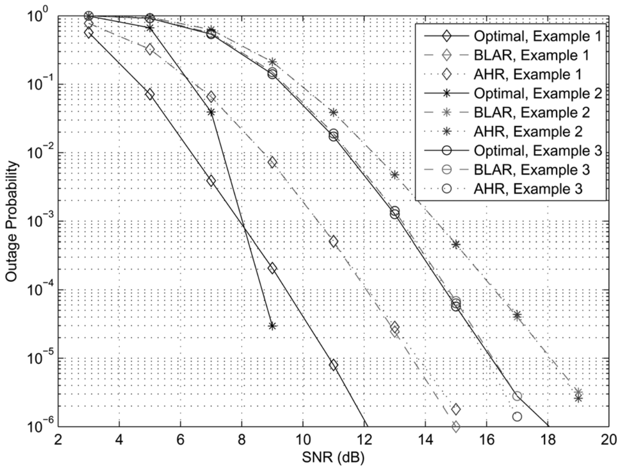


Fig. 4 *Outage comparison of optimal routing, BLAR and AHR for scenario 7, R = 2 bits/s/Hz and* $\lambda_{rm} = d_m^{-3}$ *for all* $1 \le m \le M$

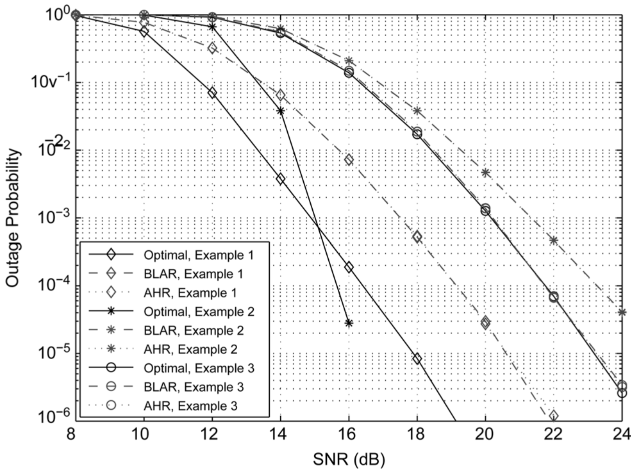


Fig. 5 *Outage comparison of optimal routing, BLAR and AHR for scenario 7, R = 4 bits/s/Hz and* $\lambda_{rm} = d_m^{-3}$ *for all* $1 \le m \le M$

first hop and the last hop, example 2 has the smallest outage probability over the three examples and the outage curve of example 2 goes eventually under that of example 1. Compared with the outage curve of example 1 and example 3, the outage curve of example 2 has a much steeper slope, which means a higher diversity at the shown SNR regime. This can be explained as the result of a shorter distance: the shorter the distance in the first hop and the last hop, the higher λ_1 and λ_M, the lower the SNR regime where the full diversity shows up. This also explains why in example 3 the diversity order of optimal routing is almost equal to that of the AHR and BLAR routing.

6 Conclusion

In this study, we proposed an opportunistic routing algorithm for clustered multi-hop networks that arbitrarily selects a decoding relay in the first $M-1$ hops, and only requires CSI for selection in the final hop. This algorithm was shown to achieve the same outage performance as AHR [12], and additionally achieves the maximum diversity offered by the channel for a variety of network cluster topologies. In fact, the proposed algorithm can attain the same diversity offered by an optimal scheme which requires global CSI and performs an exhaustive search over all possible routes. Furthermore, the proposed algorithm is very simple, and has the flexibility of supporting additional, higher-layer routing objectives without any loss in diversity. This algorithm has implications for the design of future multi-hop networks, as it demonstrates that full diversity can be achieved without full CSI. Future work in the area could incorporate the issue of network flows, and include multiple sources and destinations as well as the effect of interference from other transmissions.

7 References

1 Baker, D., Ephremides, A., Flynn, J.: 'The design and simulation of a mobile radio network with distributed control', *IEEE J. Sel. Areas Commun.*, 1984, **2**, (1), pp. 226–237

2 Lin, C., Gerla, M.: 'Adaptive clustering for mobile wireless networks', *IEEE J. Sel. Areas Commun.*, 1997, **15**, (7), pp. 1265–1275

3 Banerjee, S., Khuller, S.: 'A clustering scheme for hierarchical control in multi-hop wireless networks'. Proc. IEEE Conf. Computer and Communications Societies (INFOCOM 2001), April 2001, vol. 2, pp. 1028–1037

4 Couto, D.S.J.D., Aguayo, D., Bicket, J., Morris, R.: 'A high-throughput path metric for multi-hop wireless routing', *Wirel. Netw.*, 2005, **11**, pp. 419–434, 10.1007/s11276-005-1766-z, available at http://dx.doi.org/10.1007/s11276-005-1766-z

5 Obaidat, M.S., Dhurandher, S.K., Jindal, P., Chavli, R., Valecha, S.: 'PMH: a stability based predictive multi-hop routing protocol for vehicular *ad hoc* networks', *J. Internet Technol.*, 2010, **11**, (4), pp. 437–449

6 Pandana, C., Siriwongpairat, W., Himsoon, T., Liu, K.: 'Distributed cooperative routing algorithms for maximizing network lifetime'. Proc. IEEE Wireless Communications and Networking Conf. (WCNC'06), April 2006, vol. 1, pp. 451–456

7 Li, F., Wu, K., Lippman, A.: 'Energy-efficient cooperative routing in multi-hop wireless *ad hoc* networks'. Proc. IEEE Int. Performance, Computing, and Communications Conf. (IPCCC'06), April 2006, pp. 215–222

8 Babaee, R., Beaulieu, N.: 'Cross-layer design for multihop wireless relaying networks', *IEEE Trans. Wirel. Commun.*, 2010, **9**, (11), pp. 3522–3531

9 Boyer, J., Falconer, D., Yanikomeroglu, H.: 'Multihop diversity in wireless relaying channels', *IEEE Trans. Commun.*, 2004, **52**, (10), pp. 1820–1830

10 Chen, S.-H., Mitra, U., Krishnamachari, B.: 'Cooperative communication and routing over fading channels in wireless sensor networks'. Proc. Int. Conf. on Wireless Networks, Communications and Mobile Computing (WiCOM'05), June 2005, vol. 2, pp. 1477–1482

11 Tian, Q., Bandyopadhyay, S., Coyle, E.J.: 'Designing directional antennas to maximize spatio-temporal sampling rates in multi-hop clustered sensor networks', *J. Internet Technol.*, 2007, **8**, (1), pp. 1–10

12 Gui, B., Dai, L., Cimini, L.: 'Routing strategies in multihop cooperative networks', *IEEE Trans. Wirel. Commun.*, 2009, **8**, (2), pp. 843–855

13 Azimi-Sadjadi, B., Mercado, A.: 'Diversity gain for cooperating nodes in multi-hop wireless networks'. Proc. IEEE Vehicular Technology Conf. (VTC'04), 2004, Vol. 2, pp. 1483–1487

14 Lin, I.-T., Sasase, I.: 'Distributed *ad hoc* cooperative routing in cluster-based multihop networks'. Proc. IEEE Intl. Symp. on Personal, Indoor and Mobile Radio Communications (PIMRC'09), September 2009, pp. 2643–2647

15 Biswas, S., Morris, R.: 'ExOR: opportunistic multi-hop routing for wireless networks', *SIGCOMM Comput. Commun. Rev.*, 2005, **35**, pp. 133–144

16 Zeng, K., Lou, W., Yang, J., Brown, D.: 'On throughput efficiency of geographic opportunistic routing in multihop wireless networks', *ACM Mobile Netw. Appl. (MONET)*, 2007, **12**, (5), pp. 347–357

17 Tse, D., Viswanath, P.: 'Fundamentals of wireless communication' (Cambridge University Press, 2005)

18 Bletsas, A., Khisti, A., Reed, D., Lippman, A.: 'A simple cooperative diversity method based on network path selection', *IEEE J. Sel. Areas Commun.*, 2006, **24**, (3), pp. 659–672

19 Yang, S., Belfiore, J.: 'Diversity of MIMO multihop relay channels', *IEEE Trans. Inf. Theory*, 2007 submitted to, available at http://arxiv.org/PS_cache/arxiv/pdf/0708/0708.0386v1.pdf

20 Toh, C.-K.: 'Maximum battery life routing to support ubiquitous mobile computing in wireless *ad hoc* networks', *IEEE Commun. Mag.*, 2001, **39**, (6), pp. 138–147