Mobile Netw Appl (2006) 11:593–611
DOI 10.1007/s11036-006-7324-9

On-demand diversity wireless relay networks*

JaeSheung Shin · Kyounghwan Lee · Aylin Yener · Thomas F. La Porta

Published online: 4 May 2006

Abstract There has been much recent attention on using wireless relay networks to forward data from mobile nodes to a base station. This network architecture is motivated by performance improvements obtained by leveraging the highest quality links to a base station for data transfer. With the advent of agile radios it is possible to improve the performance of relay networks through intelligent frequency assignments. First, it is beneficial if the links of the relay network are orthogonal with respect to each other so that simultaneous transmission on all links is possible. Second, diversity can be added to hops in the relay network to reduce error rates. In this paper we present algorithms for forming such relay networks dynamically. The formation algorithms support intelligent frequency assignments and diversity setup. Our results show that algorithms that order the sequence in which nodes join a relay network carefully, achieve the highest amount of diversity and hence best performance.

Keywords Wireless relay networks · Network formation · Diversity · Cellular networks

* This research is supported in part by NSF grant CNS-0508114.

J. Shin (✉) · K. Lee · A. Yener · T. F. L. Porta
Networking and Security Research Center, The Pennsylvania State University,University Park,PA 16802
e-mail: jxs958@psu.edu

K. Lee
e-mail: kxl251@psu.edu

A. Yener
e-mail: yener@ee.psu.edu

T. F. L. Porta
e-mail: tlp@cse.psu.edu

1. Introduction

Mobile nodes in traditional wireless cellular networks communicate through centralized base stations (BS) in a predefined spectrum. To improve the performance of such cellular networks, several studies on wireless relay networks, also called hybrid wireless networks, have been undertaken [1–4]. These solutions leverage the presence of persistent resources to support relay networks, and therefore rely on the fact that relay networks are always in existence.

We consider a multi-hop wireless cellular network comprised of agile radios in which relay networks are *dynamically formed* when performance on the radio access network is degraded. The spectrum for each relay network is allocated dynamically. In this way, multiple non-interfering relay networks may operate in parallel through the use of agile radios.

Because of the dynamic nature of these systems, the continuous existence of relay networks cannot be guaranteed. The spectrum on which a relay operates may be leased for a limited time. When network performance improves, or the spectrum on which it is operating is reclaimed, a relay network is dissolved and all nodes operate using the cellular interface once again. This motivates the need for an explicit procedure for mobile nodes forming a relay network. Figure 1 shows an example in which several groups of nodes form relay networks to a BS. In this example, two relay networks operating on different spectrums are formed in the cell.

In this paper we consider new algorithms that support the formation of relay networks utilizing multiple frequency bands. We are motivated by the vision of agile radio technology where multiple frequency bands can be exploited between the mobile nodes. The multiple orthogonal bands may be used to construct relay networks comprised of non-interfering links so that multiple nodes within range of each

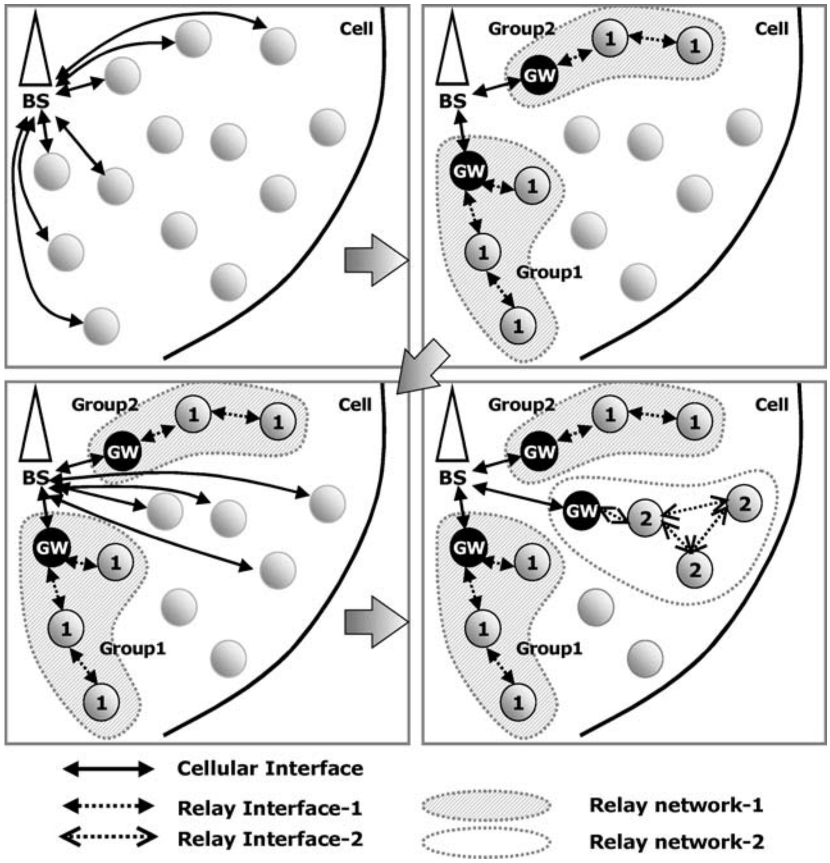


Fig. 1 Example of relay network formation

other may transmit simultaneously on different channels without relying on a MAC protocol or distributed scheduling algorithm to resolve contention.

Furthermore, the availability of multiple frequencies allows the mobile nodes to form diversity paths between each other. Path diversity helps reduce the bit error rate, and increase the throughput. The broadcasting nature of the wireless medium enables an intermediate relay node to overhear the data broadcasted by the source, which then relays the information to the destination on a new frequency band. Such relay-assisted schemes have been attracting much interest recently due to the performance improvement they provide [5–10].

We posit that network formation algorithms that exploit diversity provided by the physical channel and intelligent resource allocation lead to better end-to-end performance. We investigate five algorithms for forming relay networks in which mobile nodes communicate over multiple frequency bands and exploit two-hop diversity path when possible. We compare the performance of these algorithms based on the quality of the resulting relay networks considering end-to-end error rate, percentage of non-interfering hops on each path, and percentage of hops with diversity on each path. We show that using simple algorithms which allow local nodes to make frequency assignments based on limited information can achieve high performance. Our results show that network formation algorithms which enforce some order in assigning frequencies are more effective than those that allow nodes to randomly join the relay network.

In this paper, we make the following contributions:

- We present a network model for a multi-hop wireless cellular network in which relay networks operating in different spectrum are dynamically formed and removed. Mobile nodes in each relay network can exploit multiple frequency bands so that they can transmit or receive data simultaneously on non-interfering links even if they are within transmission range of each other.
- We develop relay network formation algorithms for such an environment for the first time. These algorithms provide frequency assignments to establish non-interfering links between mobile nodes. Moreover, they allow the mobile nodes to establish two-hop diversity paths between adjacent nodes to reduce bit error rate and increase throughput.

The rest of the paper is organized as follows. In Section 2, we briefly discuss related work in this area. In Section 3, we present the basic relay network formation algorithms and the architecture and properties of dynamic multi-radio, multi-hop wireless cellular networks. In Section 4 we extend these algorithms to accommodate diversity and multiple frequencies per relay network. In Section 5, we derive the end-to-end error probability of the network as a performance metric. In Section 6, we evaluate the performance of the network schemes by providing simulation results. In Section 7, we discuss the related issues of the paper. We conclude the paper in Section 8.

2. Related work

In the following subsections we briefly review previous work on multi-hop wireless networks and diversity in such networks.

2.1. Multi-hop wireless cellular networks

Work on multi-hop wireless networks can be broadly grouped into two areas: those that consider a single frequency on which the network operates, and those which propose to use multiple frequencies. Studies show that an equivalent service can be provided to the end-user with a reduced base station density if wireless relays are used for multihopping, thus reducing the infrastructure cost [11, 12]. Moreover, the spectral efficiency of currently deployed single hop systems can also be significantly improved. The practicality of multi-hop traffic relaying is justified according to these cost models.

There has been a great deal of work on single frequency multi-hop wireless networks to improve cellular network performance [1–4]. We are particularly interested in the third generation (3G) wireless environment in which the sharing of communication resources is done via a combination of regulating power and time division multiplexing. For example, in the 1xEV-DO system, the BS schedules only a single node for downlink transmission at any instant, and transmits at full power. The bit rate achieved during each time interval depends on its signal quality to the mobile node, which is a function of distance. If the BS can schedule nodes with better signal quality more often, then a higher average bit rate for the network can be achieved.

To maximize the throughput of such networks, the UCAN [4] system proposes that the BS transmit all downlink data to mobile nodes with high signal quality, and that these nodes then forward data to other nodes in the network through a high speed relay network operating in a different spectrum than the 3G interface, specifically using an 802.11 network. In this way, the downlink from the BS can always run at its maximum rate and all users achieve higher throughput. It is reported that UCAN can achieve improvements of the average and maximum throughput of up to 82% and 37%, respectively. This work assumes that a persistent 802.11 network exists for use as the relay network.

Recently, there has been a great deal of effort on advanced wireless networks in which nodes are able to simultaneously communicate with their neighbors using multiple radios/interfaces over multiple orthogonal channels [13–15]. In [15] it is shown that we can asymptotically achieve optimal network capacity by using multiple interfaces and that the network throughput can be significantly improved when mobile nodes are equipped with multiple interfaces and enabled to utilize multiple channels even if mobile nodes have smaller number of radio interfaces than the number of available channels. In order to form multiple orthogonal links efficiently, several channel assignment schemes are proposed in [13, 14].

These previous efforts differ from ours in two key ways. First, they do not consider path diversity. Second, they are designed for ad hoc or mesh networks, and do not, therefore, rely on neither ordering of requests to improve the efficiency of frequency assignments nor base station broadcasts to disseminate information.

2.2. Wireless diversity relay networks

An intense research effort is currently being directed to understanding the performance limits of *wireless relay networks* [5–7]. To increase the transmission range and capacity of wireless ad-hoc networks, data packets can be delivered to the destination not only by a direct link, but by one or more diversity paths with the help of intermediate relay nodes. Such relay assisted communication systems are shown to achieve the benefits of spatial diversity without requiring physical antenna arrays [8–10].

In wireless relay networks, the relay node overhears the data from the source, performs appropriate signal processing of the received data, and forwards the data to the destination. The destination combines the received signals from the source and the relay to achieve a higher data rate. Realistic scenarios require orthogonality between the transmission from the source and the relay to avoid the need for simultaneous transmission and reception at the relay. This orthogonality can be realized by frequency division [16–18, 27] time division [5, 7, 8, 19] or code division [9, 10].

Methods of forwarding the data at the relay include the so called amplify and forward (AF), and decode and forward (DF) schemes [8, 20–22]. In AF, the relay simply amplifies what it receives from the source and forwards it to the destination. In DF, the relay decodes the signal from the source and re-encodes and forwards the newly encoded data to the destination. As long as there is no decoding error at the relay, DF performs better than AF because the destination can receive the two identical signals from the diversity paths [20]. The possibility of a decoding error is low for reasonably large received signal-to-noise ratio (SNR) values at the relay. If the SNR is not large, the signal may be decoded in error, and DF can perform worse than AF [20]. In order to prevent this error propagation, the relay nodes typically employ a threshold rule [20, 21] by which they decide to perform DF only when the received SNRs are larger than a threshold. We note that DF needs to be employed when the nodes use different frequencies on successive links because the signal from one frequency band has to be decoded and re-encoded for the different frequency band. Thus in this paper, we consider the case where all relay nodes employ DF.

3. Base relay network formation algorithms

In this section we present the basis for our relay network formation algorithms and protocols. As described in this section, these algorithms address the formation of relay networks each of which operates in a single frequency band. In Section 4, we extend these algorithms to provide frequency assignments for each link, and to build diversity hops when possible in an environment in which relay networks operate on multiple frequencies simultaneously. The details and an evaluation of these base algorithms are available in [23].

A relay network is formed in two phases. In Phase I, a gateway (GW) node is chosen for each group. If the BS has spectrum available on which to form one or more relay networks, this information is broadcast over the cellular control channels so all nodes within the cell receive it simultaneously. The transmission radius of a node on the relay network is very small compared to the cellular coverage. Thus, a relay network generally consists of several isolated groups of mobile nodes such as relay network 1 in Fig. 1. Each group needs at least one GW node to act as a bridge between the BS and the group. To select GW nodes, every node initially broadcasts a neighbor advertisement (*NADV*) message with a Time-To-Live (TTL) value of 1. The *NADV* message contains the identification of the source node and its received signal quality from the BS. When a node receives *NADV* message from its neighbors, it compares its signal quality with the BS with its neighbor's. If the node has the best signal compared to all neighbors, the node acts as a GW node.

In Phase II, the nodes join the relay network by forming a path through one of the GWs to the BS. We consider several algorithms for this phase to overcome high contention or overload at the GW nodes which may occur if all nodes attempt to join the relay network simultaneously. We use a modified version of AODV as the ad hoc routing protocol to find the path from the mobile nodes to the BS. When an intermediate node forwards a route request (*RREQ)* message, it appends its identification and its distance from the BS to the message. Thus, when receiving the *RREQ*, the GW node can learn members within the relay network.

We leverage two optimization features of AODV and DSR to reduce the overhead of forming relay networks. First, a node may *passively learn a route* to a destination, for example if it is part of a longer path to that destination. In this case it will not launch its own *RREQ*. Second, a node that has previously learned a route may *immediately return this route* in response to a request without a further search. These two features can greatly reduce the number of messages required to find routes.

Each of the network formation algorithms uses the location information of the nodes to varying degrees to schedule control messages during network formation. These schemes are No Wait (NW—all nodes attempt to find paths simultaneously), Furthest First (FF—furthest node in the cell launches a *RREQ* first), Nearest First (NF—nearest node in the cell launches a *RREQ* first), Locally Furthest one First (LFF—furthest node within a group launches a *RREQ* first), and Region-based LFF (R-LFF—nodes in the furthest region of a group launch a *RREQ* first). Figure 2 shows an example of each formation algorithm. For details, refer to [23].

Besides NW, all of the algorithms use some node-ordering when scheduling *RREQs* to leverage passive route learning and immediate responding to reduce network formation overhead. Each scheme exploits a different amount of parallelism in discovering routes. In general, more parallelism leads to lower network formation latency but more messages (overhead) related to network formation. FF and NF are the most extreme in terms of enforcing an ordered schedule and leveraging the routing optimizations. Neither FF nor NF is feasible to implement accurately because of the difficulty of every node obtaining an absolute position of all other nodes in the relay network.

While FF and NF reduce the number of routing messages flooded in the network, mobile nodes may experience long latency due to the strict, sequential scheduling. To get the benefits of FF and NF, and the potential low latency of NW through parallelism, we propose LFF. In this scheme, the nodes furthest from the BS within each group, called starting nodes, will launch route discoveries first. All starting nodes in the cell initiate a route discovery simultaneously, thus several paths will be discovered in parallel.

LFF may still incur high latency with an increase in the node density in the cell. At high node density, more nodes are within transmission range of each other resulting in a fewer number of groups in the cell, and hence, fewer paths discovered in parallel. In order to increase the parallelism of LFF, we propose R-LFF scheme. In this scheme, the path from a starting node to a GW node in each group is divided into pre-defined regions. All nodes in the same region initiate a route discovery simultaneously.

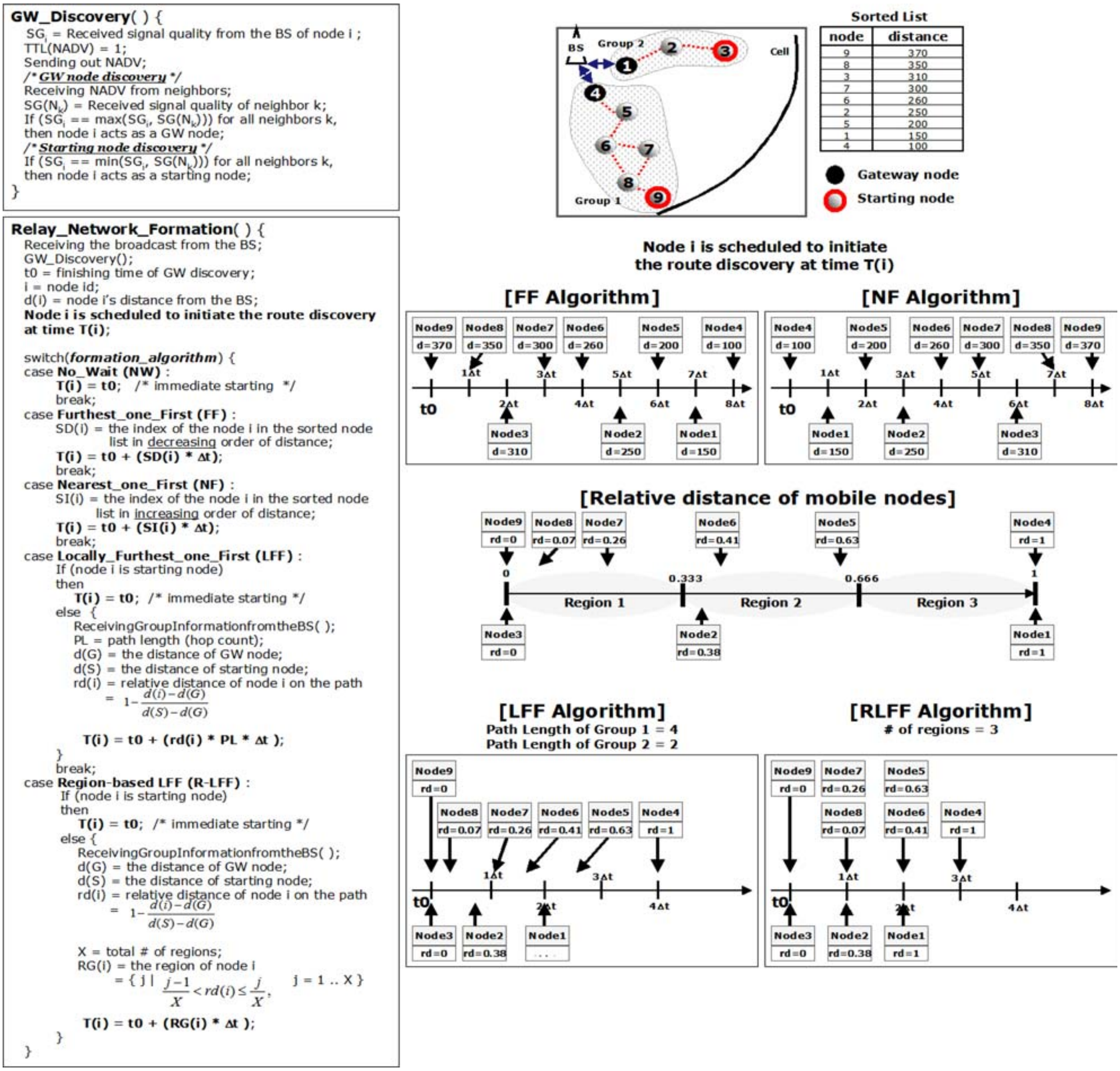


Fig. 2 Algorithm and example of relay network formation

In [23], we compare the performance of these algorithms in terms of several metrics indicating the overhead of the relay network formation and the efficiency of the resulting relay networks. For formation overhead we consider latency, signaling traffic generated, and load at the GW nodes during the formation process. To evaluate the efficiency of the resulting relay networks, we consider the average length of the paths from the nodes in the relay network to the GW nodes, and the amount of link sharing in the relay network. Link sharing is a measure of traffic aggregation in the relay network. By aggregating many flows onto links, we can have several benefits such that the number of competing and potentially interfering links is reduced. This will allow better performance from MAC layer protocols such as those used in 802.11 networks that must resolve contention across links [25, 26]. Second, if different frequencies are being assigned to each link, as the number of flows sharing links increases, fewer frequencies will be required in a relay network to achieve orthogonality between links resulting in more efficient spectrum usage. Finally, more efficient scheduling algorithms may be deployed.

The evaluation in [23] leads us to conclude that having nodes furthest from the BS initiate route discovery first is the best approach for reducing the formation overhead. Based on these observations, we extend these algorithms to form relay networks which operate using multiple frequencies simultaneously.

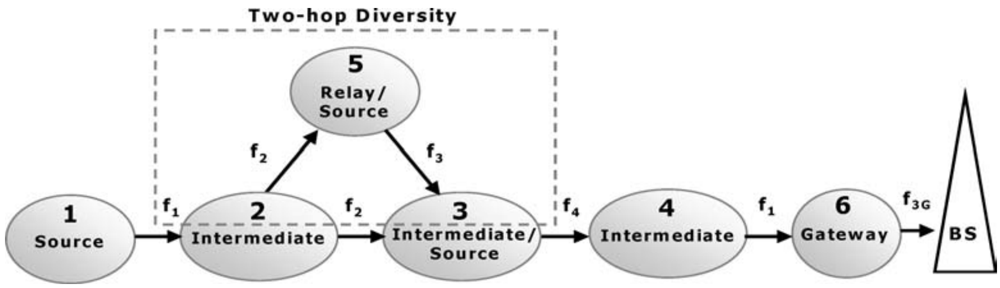


Fig. 3 Network model

4. Network formation with multiple frequencies

The network formation algorithms presented in Section 3 were designed to support relay networks operating in a single frequency. In this section we extend these algorithms in two significant ways to support relay networks comprised of multiple frequencies. The first extension assigns frequencies so that each link in the relay network is orthogonal, if possible. The second extension adds two-hop diversity, using an intermediate relay node, to each hop of the path whenever possible. The first extension allows nodes within transmission range to transmit simultaneously without requiring a MAC protocol to resolve contention, thus increasing network throughput and providing isolation of paths. The second extension provides spatial and frequency diversity, thus reducing the error rate on a path.

Our network model is shown in Fig. 3. Mobile nodes cooperate to form a relay path to a BS through a GW node. Nodes may play a combination of three roles as follows:

- ***Source*** nodes generate traffic.
- ***Intermediate*** nodes on the path forward traffic from the source to the GW.
- ***Relay*** nodes provide a two-hop diversity path between two nodes with a direct link.

Nodes may play all of these roles simultaneously. In Fig. 3, node 1 is a source. Nodes 2, 3, and 4 are intermediate nodes; node 3 is a source node as well. Node 5 is a relay node which adds two-hop diversity to the link between nodes 2 and 3; it could be also a source node. Node 6 is the GW for these nodes to the BS.

All of the network formation algorithms discussed have the following properties:

- The BS advertises the frequencies available in a relay network.
- Mobile nodes are equipped with an agile radio so that they are able to operate on all advertised frequencies.
- Even if multiple frequencies are available within each relay network, every mobile node uses a common control frequency to exchange all control messages (e.g. *RREQ*, *RREP*, *NADV*) for the network formation.
- Even if each relay network can operate on multiple frequencies, mobile node uses only one frequency to transmit data at a time, i.e., nodes do not transmit data over multiple frequencies simultaneously.
- In order to reduce the end-to-end error probability, and ultimately improve the throughput of the network, each node can use two-hop diverse paths comprised of a single relay node. In Fig. 3, node 2 transmits data to node 3 (its next hop) on frequency f_2. This transmission is also received by node 5. Node 5 retransmits the data to node 3 on frequency f_3. Thus, node 3 receives the data twice on two different frequencies. In order to build a two-hop diversity path without any interfering links, each node should have maximum 6 available frequencies for uplink and downlink transmission of a source node.

The relay network formation schemes consist of three main phases. Phases I and II are similar in purpose to those described in Section 3 with extensions to support SNR measurement, frequency assignment, and diversity. To determine if adding diversity to a direct link will reduce an end-to-end error rate, SNR measurements are made during the phase I. Frequency assignments for both direct hops and diversity paths are made during the phase II. Finally, for certain nodes that have learned routes passively, diversity is added, if possible, during the phase III of the network formation after initial paths are established.

4.1. Phase I—GW discovery and SNR measurement

Before choosing a frequency or deciding if diversity should be added to a hop, each node calculates the local error probability given its local measured SNRs from its neighbors. Every node joining the relay network initially broadcasts a *NADV* message as part of the GW discovery. The *NADV* messages are broadcast over all available frequencies in the relay network; receivers measure and store the SNR value of all received signals in their neighbor table. For each neighbor, the table contains the ID of the node, its received signal quality from the BS, and its received SNR from the neighbor on each frequency. Based on the received signal quality from the BS for each node, the GW node is chosen.

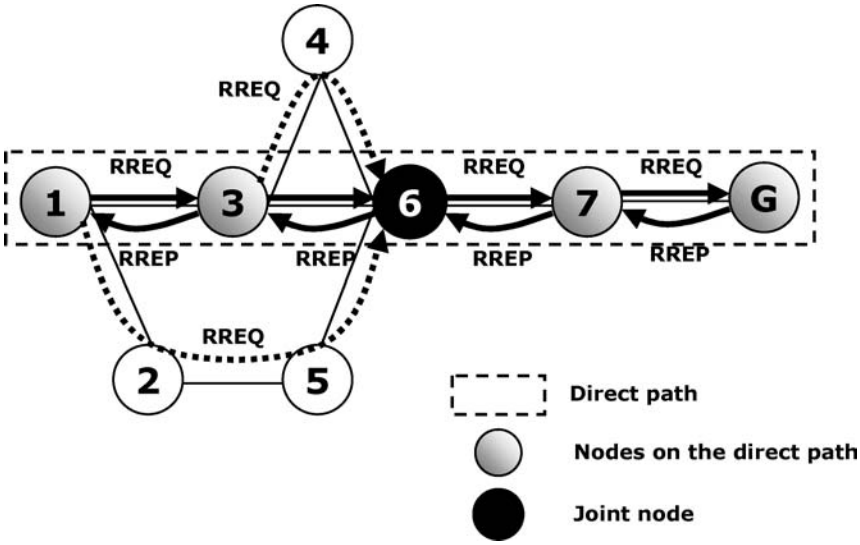


Fig. 4 Example of the direct path and joint node

4.2. Phase II—joining the relay network

In the path setup phase, the nodes join the relay network by forming a path through one of the GWs to the BS. The *RREQ* sent from a node is forwarded by several intermediate nodes to the GW. When received, the GW replies with a *RREP* back to the source. Note, the GW only replies to the first instance of the *RREQ* message from the same source. The *RREP* is delivered to the source node in reverse direction. The path established by this exchange is called the ***direct path***. If the *RREQ* is received by a node that already has a path to the GW, this node may generate an immediate *RREP* response back to the source. If there are multiple paths from the source node to the GW or replying node, some intermediate nodes on the direct path may receive several duplicates of the *RREQ* before receiving the *RREP*. These nodes are called ***joint nodes***.

Figure 4 shows an example of a direct path and a joint node. In this example, the group contains seven nodes and one GW. The *RREQ* generated by node 1 is forwarded to the GW by nodes 3, 6, and 7. The *RREP* is returned by these nodes to the source. Thus, in this case, the direct path for source node 1 consists of nodes 1, 3, 6, and 7. Since there are multiple paths from nodes 1 to 6 and from nodes 3 and 6, node 6 may receive multiple duplicates of the *RREQ* before receiving the *RREP* from node 7. As a result, node 6 detects that it is a joint node.

4.2.1. Direct hop frequency assignment

While establishing the path, a frequency must be assigned to each hop. This includes both direct hops and diversity hops. This frequency assignment is performed by intermediate nodes on the direct path. When each intermediate node receives a *RREP*, it is responsible for assigning suitable up and downlink frequencies for the link between itself and the next node on the reverse path before forwarding *RREP* to the node.

In our modified AODV protocol, the *RREQ* contains the SNR information of the uplink node, and the *RREP* contains the frequencies used by the downlink node on the reverse path. Thus, a node can determine the frequencies available for the next hop. Based on the SNR information of the next node, the node selects frequencies which have the highest SNR value over the available frequencies.

Figure 5 shows the frequency assignment algorithm and an example of the frequency assignment at node 7 in Fig. 4. In this example, we have 4 frequencies for the relay network. During the SNR measurement procedure, node 7 keeps the SNR value of all received signals and path information sent from node 6 and the GW in its neighbor table. The *RREP* sent from GW node indicates that, for the source node 1, the GW has assigned the frequency f_1 for the uplink and f_2 for downlink to the link between node 7 and GW node. Node 7 consults its routing table and neighbor table to select two frequencies for its hop to node 6. It *excludes* f_1 *and* f_2 and selects the remaining frequencies with the highest SNR value.

If the node receiving the *RREP* has no available non-interfering frequencies to choose from, it may select a frequency that is already assigned to other link. In this case, a MAC layer protocol must be used to resolve contention between the competing links, thus lowering network performance. After selecting the frequencies, the node inserts the assigned frequency information into *RREP* and forwards it to the next node on the reverse path.

4.2.2. Detecting possible diversity paths

In order to reduce the end-to-end error probability each node will add diversity to each hop of the path if possible. Here we consider two-hop diversity paths which con-

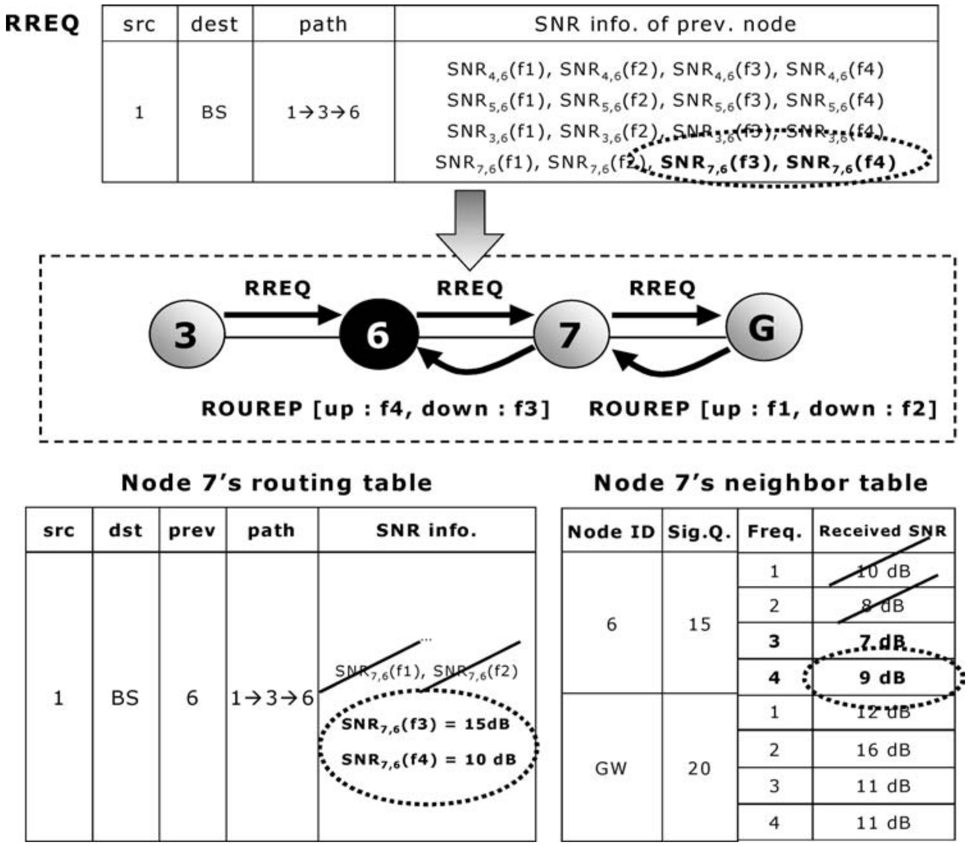


Fig. 5 Frequency assignment

sist of a direct link and one relay node. In Fig. 4, the only alternative path between two adjacent nodes with a single intermediate hop is between nodes 3 and 6 via node 4.

Based on the path information in the received *RREQs*, each joint node checks if the previous node of a *RREQ* is equal to the previous node of another *RREQ* in two-hop distance. If there is a *RREQ* satisfying the condition, there is a two-hop diverse path between the previous node on the forward path and itself. For example, in Fig. 4, node 6 receives 3 *RREQ*s. From the path information of the *RREQ*, it detects that it receives a *RREQ* from node 3 directly, and a duplicate of the *RREQ* from node 3 through node 4. Thus, it realizes that there is a two-hop diverse path between node 3 and itself.

4.2.3. *Diversity setup*

If the joint node detects a two-hop diverse path, it attempts to add a diversity path. Setting up the diversity path includes checking if there are available frequencies to be assigned to the diverse path with a link SNR above the threshold, reselecting the frequencies for the direct hop, and selecting the most suitable frequencies for the diverse path. If there is no available frequency for the diverse path, then diversity is not established.

During the initial direct hop frequency assignment procedure, the up and downlink frequencies which have the highest SNR value of the direct hop over the available frequencies are selected. However, in order to maximize the benefits of diversity, the joint node reselects the uplink frequency, f_u, which has the highest SNR value of the hop from the next node on the reverse path to the relay node instead of the direct hop. In the same way, it reselects downlink frequency, f_d, which has the highest SNR value of the hop from itself to the relay node.

Then, the joint node selects the uplink frequency for the relay node, $f_{\mathrm{u-relay}}$, which has the highest SNR value of the hop from the relay node to itself, and the downlink frequency for the relay node, $f_{d-relay}$, which has the highest SNR value of the hop from the relay node to the next node on the reverse path. If diversity is established, the joint node inserts the assigned frequency information into the *RREP* and forwards it the next node. It also sends *RREP* to the relay node.

4.3. Phase III—Adding diversity to the relay node

Relay nodes may act as a source node as well as shown in Fig. 3. When receiving the *RREP* from the joint node at the end of diversity setup procedure, the relay node passively learns a route to the GW. Therefore, the relay node may not participate in the procedures to establish a diversity hop

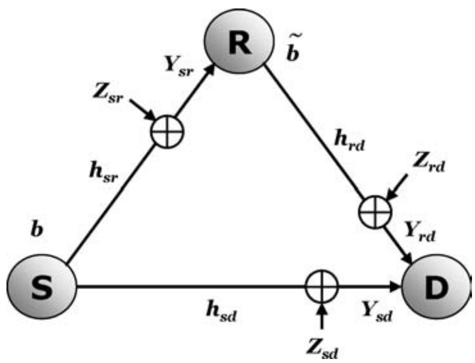


Fig. 6 Three-node relay network with two-hop diversity

from itself to the joint node. In order to get improved network performance, the joint node can add diversity for the relay node in this phase.

In order to do this, the joint node assigns up and downlink frequencies and establishes diversity in the same way described in the previous section. While this phase is logically separate from the path setup phase, the joint node can perform these procedures simultaneously with setting up a diverse path in the previous phase. Thus, the joint node can insert all assigned frequency information for two diverse paths into the *RREP* and forward it the next node and the relay node.

While this procedure complicates path setup, it provides performance improvements discussed in Section 7.

5. Error probability analysis for the relay network

Once the specific frequency channels are assigned between the source node and the gateway node, the paths in the relay network will be a combination of interfering direct hops, non-interfering direct hops, and diversity hops depending on whether the intermediate relays choose to perform DF or not. In this section, we provide the error probability as a performance metric. In this regard, we assume that either a MAC protocol or distributed scheduling algorithm arbitrates the interfering hops, and so that for the purposes of error rate, these links can be treated as simple non-diversity links.

We start with the error probability of the three-node relay network with two-hop diversity as shown in Fig. 6. We consider the scenario where binary phase-shift keying (BPSK) is employed at each node along with the appropriate detection schemes, i.e., maximum-likelihood (ML) detection at the relay and maximum-ratio combining (MRC) at the destination [24]. We assume that our channels are quasi-static. The noise terms, Z_{sd}, Z_{sr}, Z_{rd}, are independent and identically distributed Gaussian random variables with zero-mean and variance[1] 1/2. The input-output signal model is given by

$$Y_{rd} = h_{rd}\tilde{b} + Z_{rd} \quad (1)$$

$$Y_{sd} = h_{sd}b + Z_{sd} \quad (2)$$

$$Y_{sr} = h_{sr}b + Z_{sr} \quad (3)$$

where b denotes the transmitted bit from the source that is equiprobable to be 1 or -1, and $\tilde{b}$ is the transmitted bit from the relay that is either b or $-b$ depending on the correctness of decision at the relay. Y_{rd} denotes the received signal at the destination node from the relay node, and Y_{sd} is the received signal at the destination node from the source node. We also denote Y_{sr} as the received signal at the relay node from the source node. We assume that the effect of the transmitted power and noise power are taken into account in the channel gains, h_{sr}, h_{sd}, and h_{rd}.[2] We define the received SNR at the each node given by

$$\gamma_{sr} = h_{sr}^2, \quad \gamma_{sd} = h_{sd}^2, \quad \gamma_{rd} = h_{rd}^2 \quad (4)$$

Considering the possibility of the decoding error at the relay, the error probability is given by

$$P_e = \begin{cases} 1 - P^d_{c|\gamma_{sr}\geq\gamma_{\text{th}}} & \text{if } \gamma_{sr} \geq \gamma_{\text{th}} \\ Q\left(\sqrt{2\gamma_{sd}}\right) & \text{if } \gamma_{sr} < \gamma_{th} \end{cases} \quad (5)$$

where γ_{th} is the received SNR threshold at the relay for initiating DF operation. The error probability of BPSK is expressed as $Q(\sqrt{2SNR})$ where $Q(x)$ is the Gaussian tail function defined by [24]

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-u^2/2} du \quad (6)$$

When $\gamma_{sr} \geq \gamma_{\text{th}}$, the correct decision probability at the destination is given by

$$P^d_{c|\gamma_{sr}\geq\gamma_{th}} = P^r_c P^d_{c|\text{correct at relay}} + P^r_e P^d_{c|\text{error at relay}} \quad (7)$$

where P^r_c is the correct decision probability at the relay, $P^d_{c|\text{correct at relay}}$ is the correct decision probability at the destination given that the detection at the relay is correct, $P^r_e = 1 - P^r_c$ is the error probability at the relay, and $P^d_{c|\text{error at relay}}$ is the correct decision probability at the destination given that the detection at the relay is erroneous. It can be readily shown that the error probabilities are given by

[1] For convenience we normalize the one sided power spectral density to unity.

[2] Channel gains are assumed to be real numbers throughout the paper.

$$
\begin{aligned}
P_c^r &= 1 - Q\left(\sqrt{2\gamma_{sr}}\right) \\
P_e^r &= Q\left(\sqrt{2\gamma_{sr}}\right) \\
P_{c|\text{correct at relay}}^d &= 1 - Q\left(\sqrt{2\left(\gamma_{sr} + \gamma_{sd}\right)}\right)
\end{aligned} \tag{8}
$$

where $P_{c|\text{correct at relay}}^d$ is the correct probability of MRC detection for receiving two identical signals from two diversity paths [24].

Next, we set out to find $P_{c|\text{error at relay}}^d$. If there is an error in the detection of signal from the source at the relay i.e., $\tilde{b} = -b$, the received signal at the destination is given by

$$
\begin{aligned}
Y_{rd} &= -h_{rd} b + Z_{rd} \\
Y_{sd} &= h_{sd} b + Z_{sd}
\end{aligned} \tag{9}
$$

The weights of the MRC at the destination are chosen by

$$
W_{rd} = \frac{h_{rd}}{\sqrt{h_{rd}^2 + h_{sd}^2}}, \quad W_{sd} = \frac{h_{sd}}{\sqrt{h_{rd}^2 + h_{sd}^2}} \tag{10}
$$

The sign of the variable $U = W_{rd} Y_{rd} + W_{sd} Y_{sd}$ yields the bit decision at the destination. In this scenario, it is straightforward to show that $P_{c|\text{error at relay}}^d$ is given by

$$
P_{c|\text{error at relay}}^d = \begin{cases} 1 - Q\left(\sqrt{2\gamma_{com}}\right) & \text{if } \gamma_{sd} \geq \gamma_{rd} \\ Q\left(\sqrt{2\gamma_{com}}\right) & \text{if } \gamma_{sd} < \gamma_{rd} \end{cases} \tag{11}
$$

where γ_{com} is the combined SNR at the output of MRC

$$
\gamma_{com} = \frac{\left(-\gamma_{rd} + \gamma_{sd}\right)^2}{\gamma_{rd} + \gamma_{sd}} \tag{12}
$$

Now, we have $P_{c|\gamma_{sr} \geq \gamma_{\text{th}}}^d$

$$
P_{c|\gamma_{sr} \geq \gamma_{\text{th}}}^d = \begin{cases} \left(1 - Q\left(\sqrt{2\gamma_{sr}}\right)\right)\left(1 - Q\left(\sqrt{2\left(\gamma_{sd} + \gamma_{rd}\right)}\right)\right) \\ \quad + Q\left(\sqrt{2\gamma_{sr}}\right)\left(1 - Q\left(\sqrt{2\gamma_{com}}\right)\right) \\ \quad \text{if } \gamma_{sd} \geq \gamma_{rd} \\ \left(1 - Q\left(\sqrt{2\gamma_{sr}}\right)\right)\left(1 - Q\left(\sqrt{2\left(\gamma_{sd} + \gamma_{rd}\right)}\right)\right) \\ \quad + Q\left(\sqrt{2\gamma_{sr}}\right) Q\left(\sqrt{2\gamma_{com}}\right) \quad \text{if } \gamma_{sd} < \gamma_{rd} \end{cases} \tag{13}
$$

Finally, the error probability is obtained by inserting (13) into (5).

We note that the foregoing error probability is for a single-hop three node relay network. If we have more than one hop from the source to the destination, the end-to-end error probability can be expressed as

$$
P_{e2e} = 1 - \prod_{i=1}^{N} \left(1 - P_{e,i}\right) \tag{14}
$$

where N is the total number of hops between the source and the destination and $P_{e,i}$ is the error probability at the ith hop which is given by (5). Note that in constructing (14), we assume independent errors per hop, and that the correct detection at the destination is done only when each hop decision is correct. This is obviously a pessimistic estimate for the actual end-to-end performance as intermediate bit reversals between hops may lead to a correct decision at the end. However, for clarity of exposition, we will use (14) the end-to-end error rate in our numerical results.

To justify using the diversity relay channel, we consider the example with three hops. We compare the bit error probabilities of direct transmission only, versus transmission using diversity relay nodes in Fig. 7. We assume that the received SNR threshold at each relay node is 10 dB. For the diversity case, the received SNR at each hop is 10 dB, 10 dB, and 15 dB, leading to each relay becoming diversity nodes. As expected, having the added diversity leads to a much better performance than using only the direct links.

We note that this performance gain is not always guaranteed unless we have an appropriately chosen received SNR threshold. If the received SNR threshold is not high enough, the diversity case can perform worse than the direct case, when the direct link quality is relatively good. This is because the relay with a poor link can cause error propagation. This is demonstrated in Fig. 8. Also, the quality of the link between the relay and the destination plays an important role. Since we use BPSK transmission, if there is a high error in detection at the relay and we have a better relay to the destination channel, the destination is more likely to receive an erroneous bit. However, if the relay to the destination channel is bad, the erroneous bit can be flipped back to the original correct bit. Thus, when there is high detection error at the relay, we can get better error performance as the relay to the destination link gets worse. Conversely, when there is a small error rate at the relay, a better relay to the destination link will provide better overall error probability. We set the received SNR threshold to make sure that there is low error probability at the relay. Throughout our simulations, we use 10 dB for the threshold for γ_{sr} which corresponds to a decoding error of 10^{-6} at the relay node.

Note that when using DF, if an intermediate node correctly receives a frame on the direct link, it does not need to wait to receive the data on the diversity path before forwarding. This way, latency is not increased.

6. Performance evaluation

6.1. Simulation environment

In order to evaluate the relay network formation algorithms, we simulate our protocols using ns-2. Table 1 summarizes

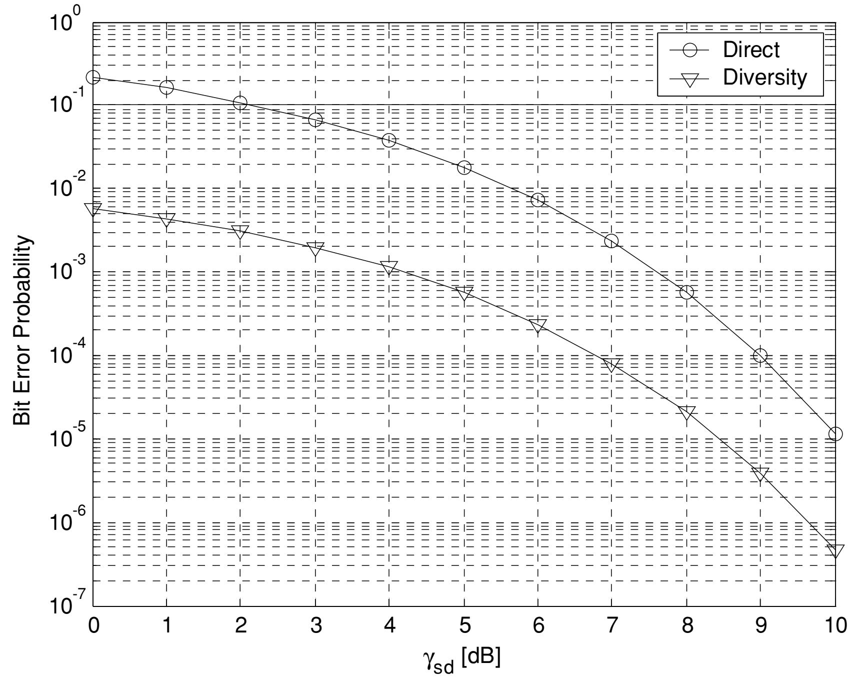


Fig. 7 Bit error probability of two schemes when the received SNR threshold is 10 dB

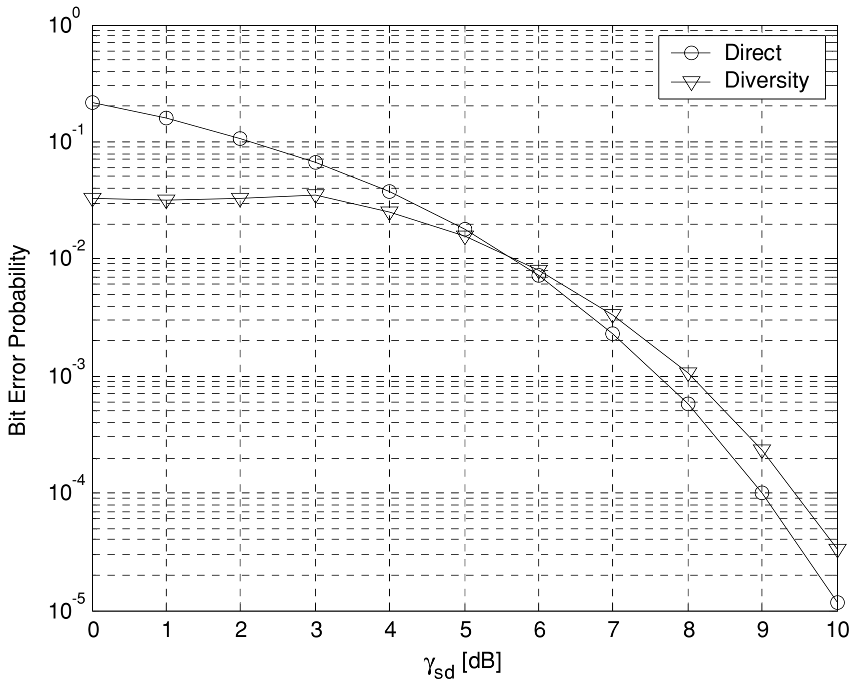


Fig. 8 Bit error probability of two schemes when the received SNR threshold is 3 dB

the simulation parameters. We use IEEE 802.11b with a 115-meter communication range as the common control frequency for delivering routing messages. The CMU scenario generation tool was used to create a network consisting of up to 80 mobile nodes within a square cell of 886 × 886 m^2. The BS is located in the center of the cell. We vary the number of frequencies available within a relay network from 8 to 12. Each simulation is run 30 sec and each data point in the result graphs is the average of 100 runs with different topologies.

6.2. Performance metrics

We evaluate each scheme against three metrics: the average end-to-end error probability of each node, the percentage of hops with diversity, and the percentage of hops with interfer-

Table 1 Simulation parameters

Variable	Value
Duration	30 sec
Runs	100 runs with different topologies
Air interface range	115 m
MAC for common control signal	802.11
Cell size (BS at center)	886 m × 886 m
Routing protocol	Modified AODV
Packet size	1500 bytes
Nodes per cell	1 → 80 nodes
Frequencies available within a relay network	8 → 12 frequencies
Δt	20 msec
Regions for R-LFF	5

ing links. All mobile nodes in the relay network except the GW nodes can be source nodes for a path; the GW nodes are always the destination for a path.

The average end-to-end error probability, $P_{ava.e2e}$, is the average error probability of all source and destination pairs in the network and is given by

$$P_{avg.e2e} = \frac{\sum_{i=1}^{S} P_{e2e,i}}{S} \tag{15}$$

where S is the number of the source nodes in the network and $P_{e2e,i}$ denotes the end-to-end error probability of the ith source and the corresponding GW node pair.

During the frequency assignment procedure, if there is no available non-interfering frequency for a node to select for a link, it will choose an interfering frequency. In this case a MAC protocol is required on the link to resolve contention in real-time. This reduces end-to-end throughput, potentially severely, as shown in [25, 26]. The percentage of hops with interfering links is defined by the average number of hops assigned an interfering frequency to the total number of hops of the path from each source node to a corresponding GW node.

$$\textit{Percentage of hops with interfering links} = \frac{\sum_{i=1}^{S} \frac{\#.\textit{ of hops with interfering links on the path from node } i \textit{ to a GW node}}{\textit{total } \#\textit{ of hops on the path from node } i \textit{ to a GW node}}}{S} \tag{16}$$

If a joint node detects a two-hop diverse path, it will select a frequency to provide diversity if one is available that meets the target SNR threshold. The *relative diversity percentage* is defined as the average ratio of the number of hops having diversity to the number of hops with possible diversity on the path from each source node to a corresponding GW.

$$\textit{Relative diversity percentage} = \frac{\sum_{i=1}^{S} \frac{\#.\textit{ of hops with actual diversity on the path from node } i \textit{ to a GW node}}{\#.\textit{ of hops with possible diversity on the path from node } i \textit{ to a GW node}}}{S} \tag{17}$$

A hop is considered to have possible diversity if a two-hop diverse path to it exists, i.e., the only reason it will not have diversity is if no frequency above the SNR threshold is available.

The *absolute diversity percentage* is defined as the ratio of number of hops with diversity to the total number of hops in a path.

$$\textit{Absolute diversity percentage} = \frac{\sum_{i=1}^{S} \frac{\#.\textit{ of hops with actual diversity on the path from node } i \textit{ to a GW node}}{\textit{total } \#.\textit{ of hops on the path from node } i \textit{ to a GW node}}}{S} \tag{18}$$

We obtained results from two different scenarios described as follows.

- Scenario I—equal SNR on each link: Every link is assumed to have the same received SNR value of 10 dB. The number of frequencies in each relay network is varied from 8–12.
- Scenario II—different SNR on each link: Each link has a random SNR value in the range between 0 dB and 20 dB. The number of frequencies in each relay network is 12.

6.3. Evaluation

In the following results, we compare the performance of the five relay network formation algorithms. As a baseline we include a case in which no diversity is added to a path. This allows us to compare the performance gains of the formation algorithms based on their ability to add diversity. These results are summarized in Table 2. We found, as expected, that given a fixed SNR value, the end-to-end error probability without diversity is proportional to the number of hops on the path from each node to the GW. Figure 9 shows the

Table 2 Average end-to-end error probability of each node without diversity

	Nodes/network			
Algorithm	10	30	50	80
NW	0.000008360	0.000011844	0.000016841	0.000024629
NF	0.000008461	0.000012391	0.000017660	0.000025147
FF	0.000008403	0.000012035	0.000016479	0.000022186
LFF	0.000008389	0.000012100	0.000016564	0.000023175
R-LFF	0.000008389	0.000012235	0.000016571	0.000023979

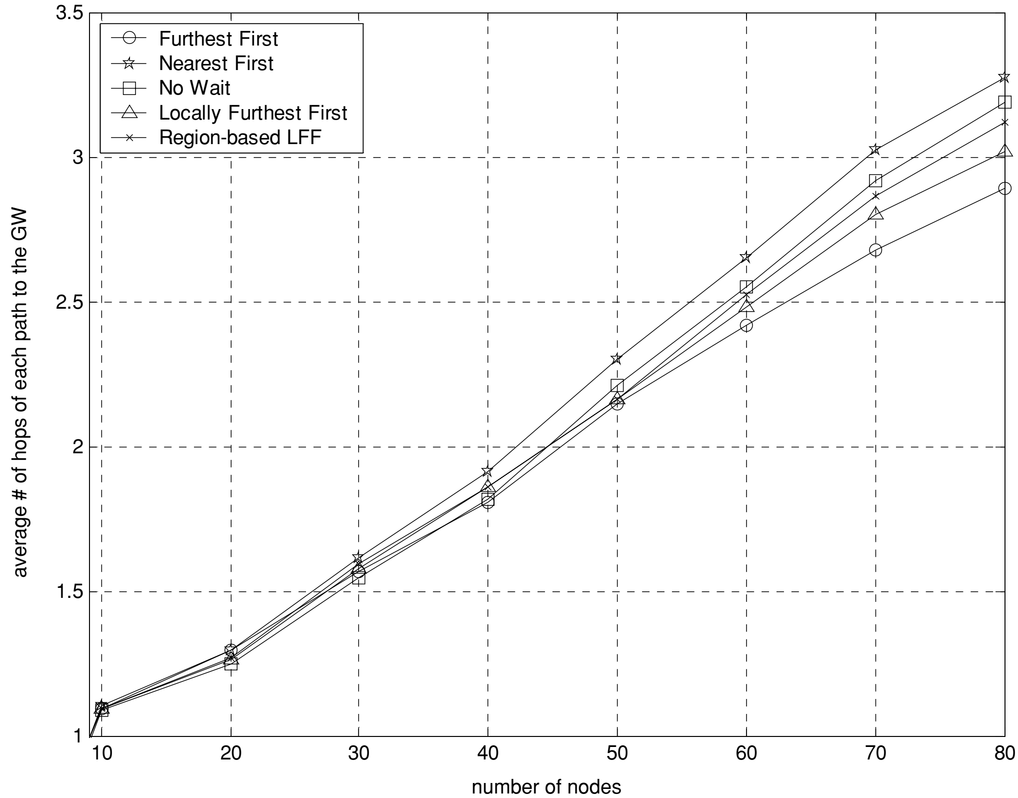


Fig. 9 Average number of hops of each path

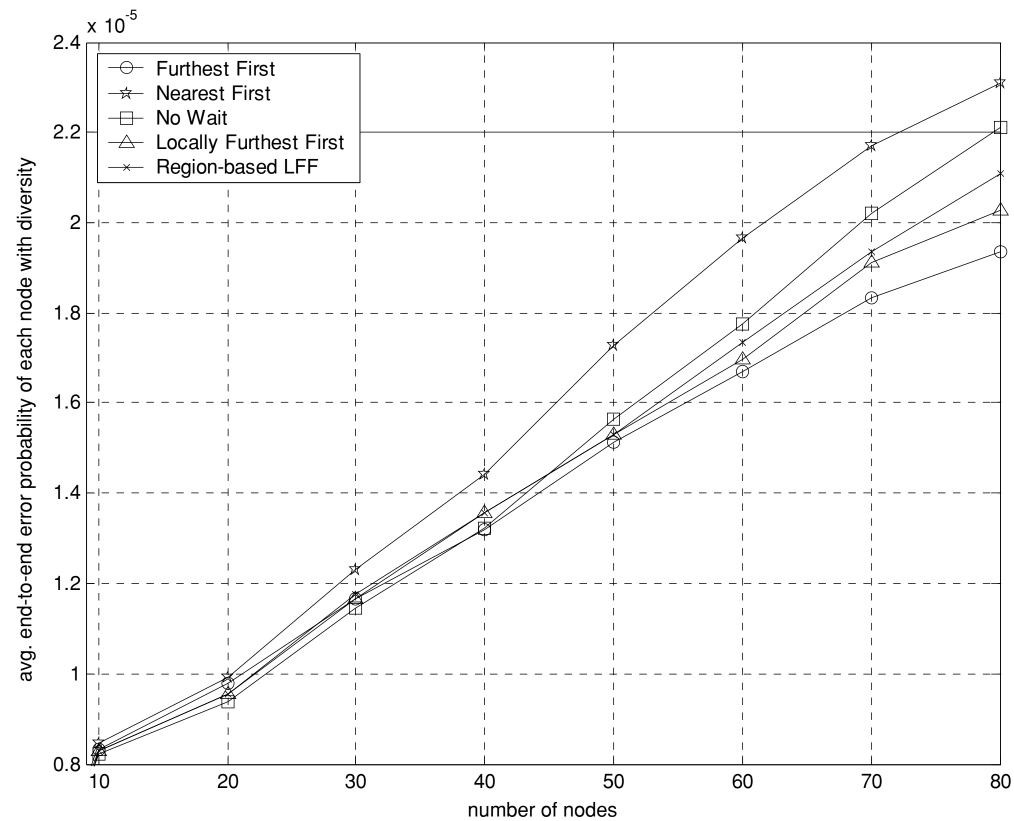
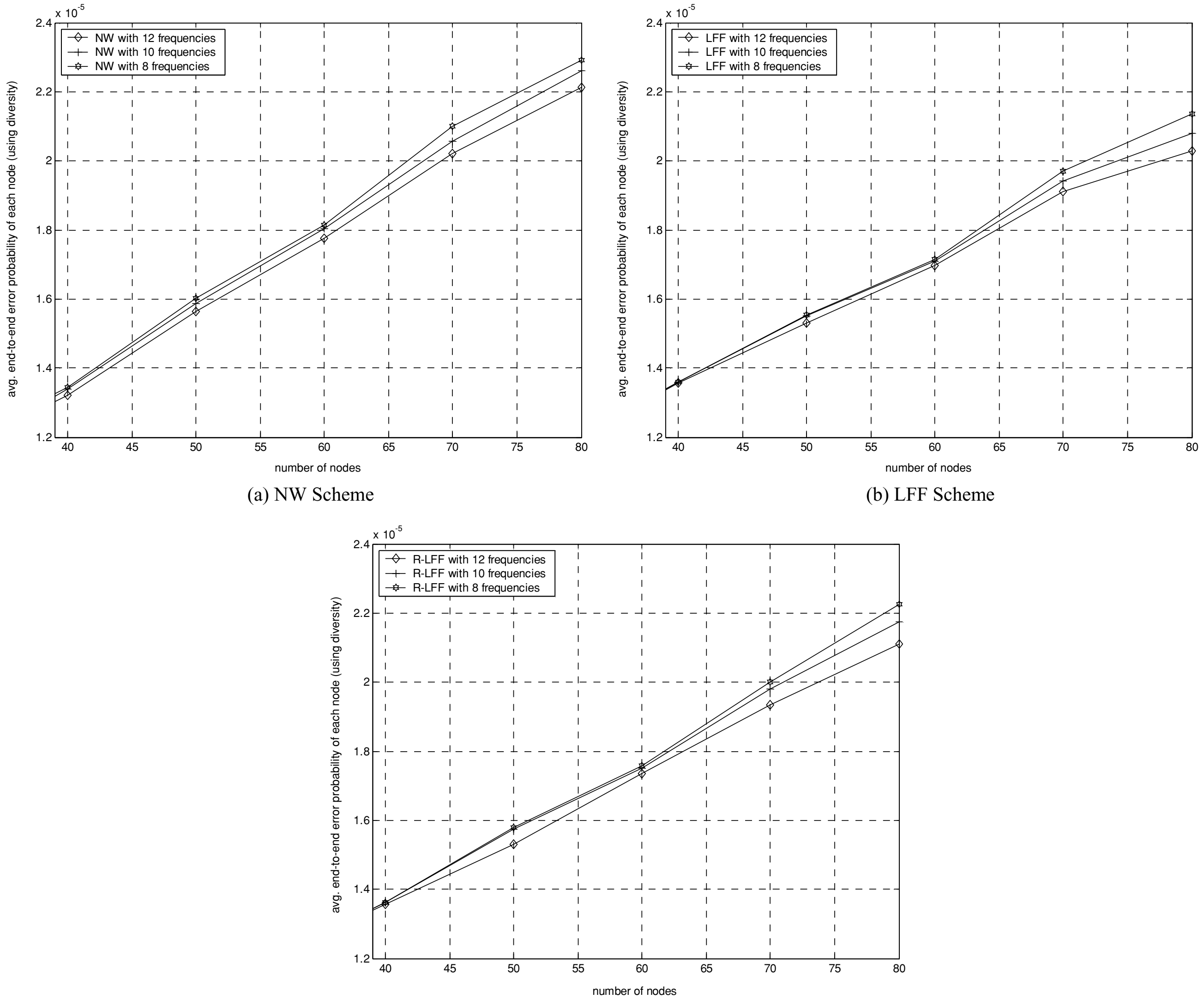


Fig. 10 Average end-to-end error probability of each node with diversity



(a) NW Scheme

(b) LFF Scheme

(c) RFF Scheme

Fig. 11 Average end-to-end error probability using diversity with various frequencies

average number of hops on the path from each node to the GW for each algorithm.

6.3.1. Scenario I

Figure 10 shows the average end-to-end error probability for all five formation algorithms versus the number of nodes in the network when diversity is included. Figure 11 shows how varying the number of frequencies available in the relay network affects the average end-to-end error probability for each node. Results for NF and FF are not shown because even if we reduce the number of available frequencies in a relay network to 8, when using these algorithms, joint nodes still have enough frequencies to achieve almost 100% diversity. This illustrates the efficiency of frequency assignments when using strict ordering in scheduling join requests. NW is affected most by the reduction in frequencies because it does not allocate the frequencies efficiently and achieves low diversity.

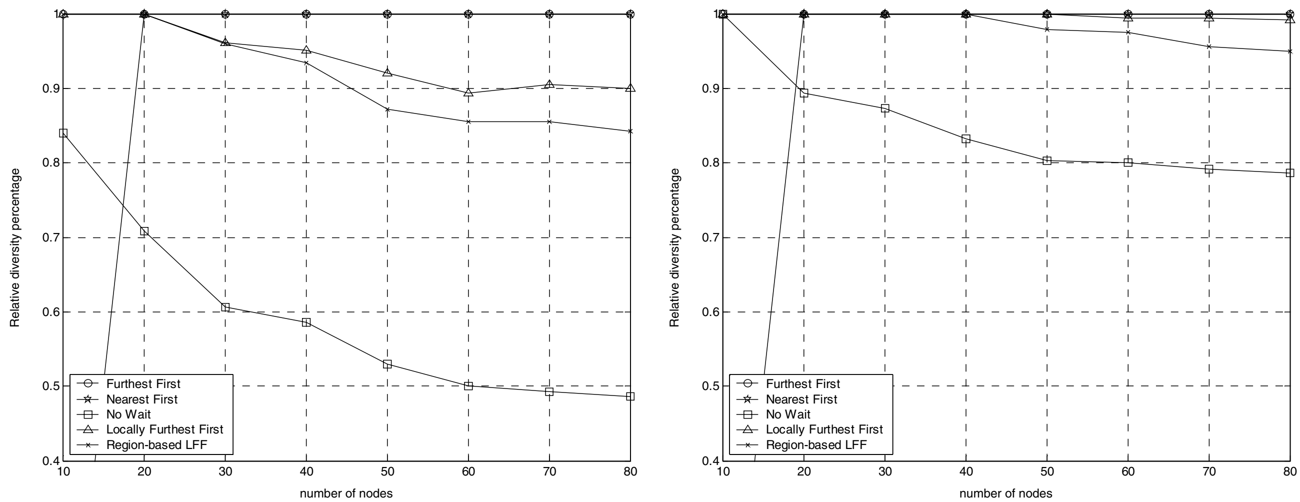
In Fig. 10, we observe that the algorithms that enforce an ordered path establishment starting with nodes furthest from the BS (FF, LFF and R-LFF) have the best performance. These results can be explained by examining Figs. 12 and 13.

As shown in Figs. 12 and 13, NW results in a low percentage of diversity hops both in a relative and absolute sense. With a small number of nodes, NW has the best performance because each node sends out its own *RREQ* which results in the shortest paths to the GW. However, as the number of nodes increases, this simultaneous broadcast of *RREQ* causes each intermediate node to receive many *RREP*s. This triggers a large number of frequency assignments resulting in few frequencies being available for diversity.

NF also performs poorly with respect to error rate. There are two reasons for this performance. First, NF tends to result in long average paths as shown in Fig. 9. Second, NF also results in relay networks with few joint nodes, and therefore does not have an opportunity to add much diversity to its paths. As shown in Figs. 12 and 13, NF achieves a high percentage of relative diversity, meaning that it assigns frequencies efficiently, but has a low percentage of absolute diversity. This latter fact is a result of having very few joint nodes and is the main reason for the high error rates.

On the other hand, with FF the node furthest from the BS establishes a direct path with diversity first, allowing intermediate nodes on this path to share the frequency assignments. Moreover, many nodes adjacent to the path also passively learn the route and this share the same path. Therefore, intermediate nodes on the direct path do not have to assign new frequencies when they act as source nodes, or when they are part of the path for a different source node. As a result, fewer frequencies are used on the direct path making more frequencies available for adding diversity. As shown Figs. 12 and 13, FF results in a relay network with both high relative and absolute diversity. As a result, FF has the lowest end-to-end error probability. In general, this is true for all of the FF-based algorithms.

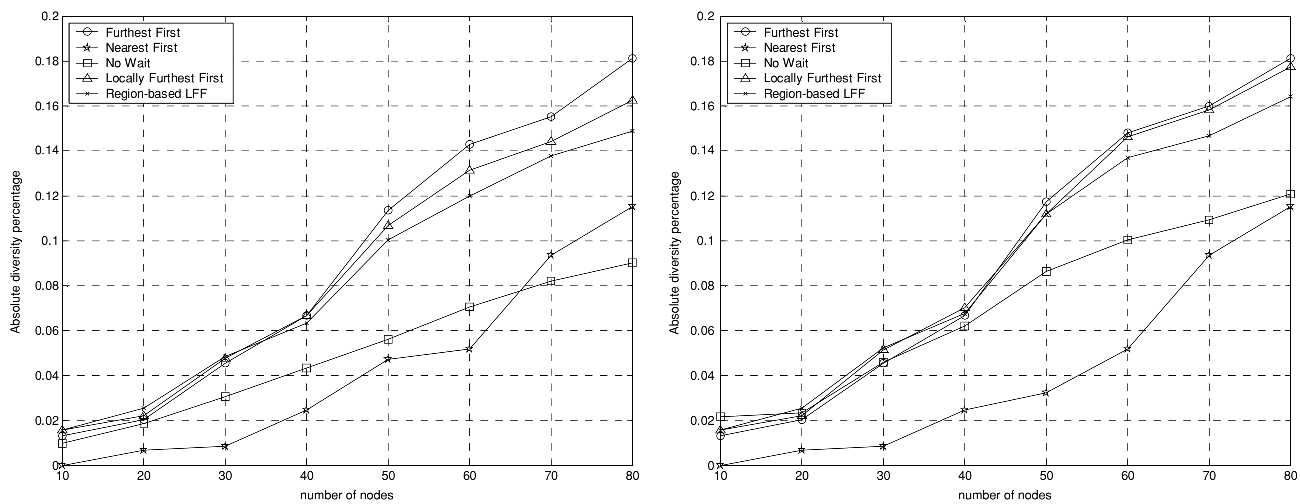
In Fig. 12, we find that the percentage of diversity is inversely proportional to the degree of parallelism of the formation algorithms. With a high degree of parallelism, many nodes send out their own *RREQ* resulting in few nodes sharing a path to the GW. The existence of multiple direct paths uses the available frequencies thus reducing diversity and increasing the number of interfering links.



(a) # of available frequencies = 8

(b) # of available frequencies = 12

Fig. 12 Relative diversity percentage on the path



(a) # of available frequencies = 8

(b) # of available frequencies = 12

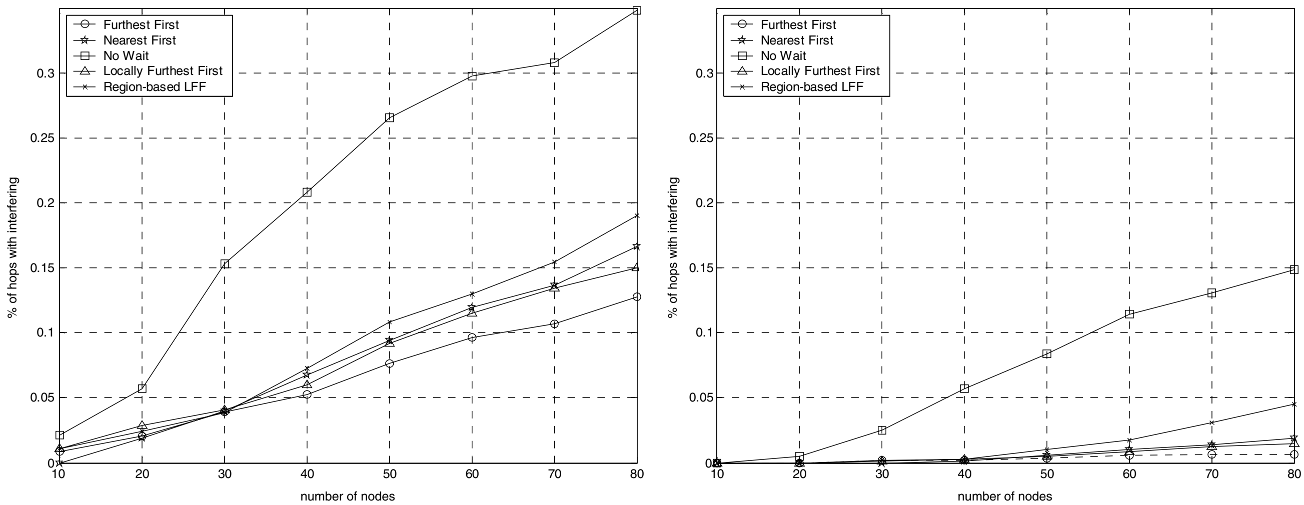
Fig. 13 Absolute diversity percentage on the path

Figure 14 shows the percentage of hops with interfering links on the path from each node to the GW node. This result shows that the ordered algorithms that perform frequency assignments in order (either nearest or furthest first) are most efficient and therefore result in fewer interfering links.

6.3.2. Scenario II

In this case, every node has a random SNR value in the range of [0, 20] dB. Therefore, diversity may not be established in some cases because no link above the SNR threshold exists over which to setup the diversity hop. However, the successful establishment of diversity will improve performance greatly because some direct hop links may have poor SNR values. Figure 15 shows the average end-to-end error probability of each node when diversity is included in the path setup.

The average end-to-end error probability depends on the SNR values of the nodes. This graph shows that we obtain similar results as those shown in Fig. 10. NF generally has



(a) # of available frequencies = 8

(b) # of available frequencies = 12

Fig. 14 The percentage of hops with interfering links

Fig. 15 Example of avg. probability of error of each node with random SNR (with diversity)

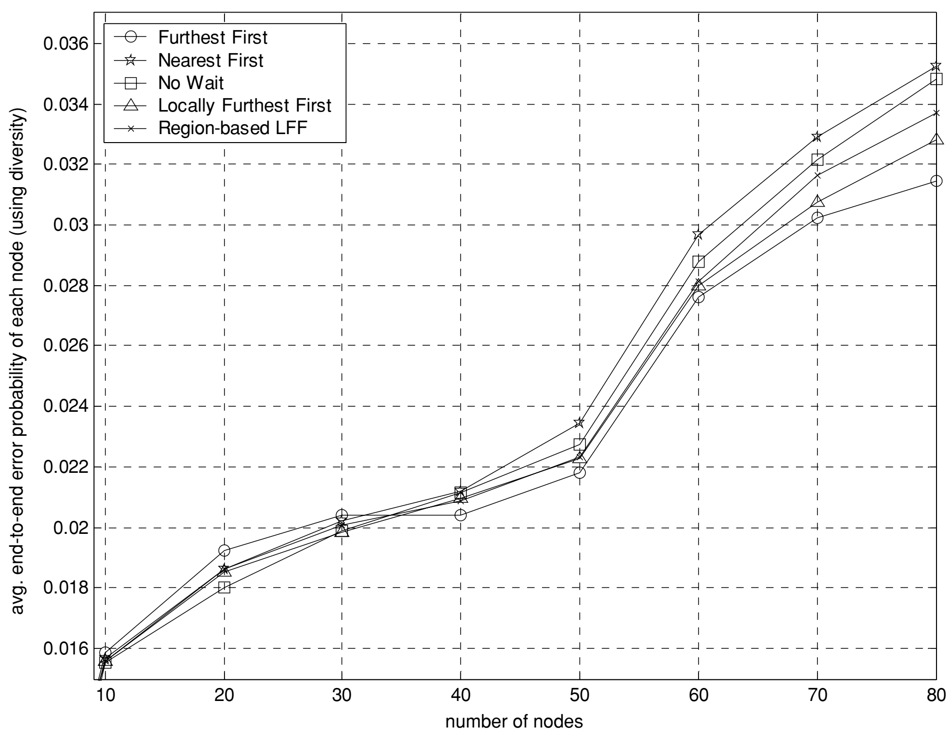


Table 3 Percentage of nodes attempting to add diversity in Phase III that are successful

Algorithm	Nodes/network 10	30	50	80
NW	100%	75%	70%	67%
NF	–	100%	100%	100%
FF	100%	100%	100%	100%
LFF	100%	100%	94%	92%
R-LFF	100%	100%	90%	83%

the highest end-to-end error probability and the FF-based algorithms have the lowest end-to-end error probability as the number of nodes increases.

7. Discussion

In the following two subsections we discuss the impact of adding diversity to relay nodes acting as sources, and optimal frequency assignments.

7.1. Adding diversity to the relay node

As discussed in Section 4, if a node passively learns a route, it will not participate in the procedures to establish a diversity hop from itself to its next hop node. If this node is acting as a relay node on a diversity hop for another path, there is the possibility that a diverse path can be established for this relay node when it is acting as a source as well. In order to add diversity to the relay node, the joint node sets up a diverse path for the relay node simultaneously when setting up a direct path for a source node. It assigns additional frequencies for uplink and downlink transmission of the relay node. Then it inserts all assigned frequency information into the RREP and sends it to the relay node as well as the next node on the reverse path.

Table 3 shows the percentage of nodes that are successful when attempting to add diversity using this method. Nodes that fail do so because there are not enough frequencies available for them to add the diversity hop. Each node that is successful will see an error rate improvement on this hop as shown in Figs. 7 and 8.

Because NW does not assign frequencies efficiently as mentioned in Section 6.3.1, it does not benefit from this phase except in cases of very small relay networks. As the number of nodes increase, the improvement of LFF and R-LFF decreases because they cannot add diversity to some relay nodes due to the lack of available frequencies. However, Table 3 shows that FF and NF algorithm do not suffer from this because they efficiently assign frequencies. Note that NF cannot add diversity when the networks size is small. In addition, even if NF can add diversity to almost all relay nodes, it has the lowest absolute diversity percentage on the path as shown in Fig. 13. In contrast, FF-based algorithms can take full advantage of this phase.

7.2. Optimality of the formation schemes

In this paper, our formation schemes are based on single-path AODV routing protocol. Thus, every node first establishes a single direct path to the GW node, and then performs frequency assignments and adds diversity where possible. In general, the direct path is the shortest path from a source node to the GW node. But, because the end-to-end error probability of the network is affected by the SNR value of each node as well as the hop count of the path, the shortest path may not be the path that yields the best performance. One possible solution is to extend path selection to multiple rounds so that several end-to-end paths may be evaluated before one is selected and committed.

Such a multi-round algorithm may also lead to more efficient frequency assignments. In the current algorithms, while returning the RREP, intermediate nodes assign the most suitable frequencies to the link for uplink and downlink transmission to the next hop with limited information as to the entire path. Thus, even if each node picks up the most suitable frequency for its own link, it may not be the globally optimal assignment. A multi-round algorithm would allow nodes to obtain more global information when performing frequency selection.

8. Conclusion

In this paper we studied the formation of relay networks for dynamic multi-radio, multi-hop wireless cellular networks. We defined five network formation algorithms to support the creation of relay networks that operate with multiple frequencies. Our algorithms assign frequencies and create diversity hops for the paths between a source node and the GW node to the BS. The frequency assignments are made to reduce the number of interfering links in the network. We compare the algorithms in terms of the average end-to-end error probability, percentage of diversity of each path, and percentage of interfering links on each path in the resulting relay networks.

We found that algorithms that order the path discovery starting with nodes furthest from the BS perform best. This is because these algorithms afford the highest amount of path sharing and therefore result in the most efficient frequency assignments.

References

1. W. Hongyi, Q. Chunming, S. De and O. Tonguz, Integrated cellular and ad hoc relaying systems: ICAR, IEEE Journal

on Selected Areas of Communications 19(10) (2001) 2105–2115.
2. G.M. Aggelou and R. Tafazolli, On the relaying capability of next generation GSM cellular networks, IEEE Wireless Communications 8(1) (2001) 40–47.
3. J. Zhou and R. Yang, Parcels: Pervasive ad-hoc relaying for cellular systems, in: *Proc. of Med-Hoc-Net*, Sardegna, Italy (2002).
4. H. Luo, R. Ramjee, P. Sinha, L. Li and S Lu, UCAN: Unified cellular and ad-hoc network architecture, in: *Proc. of ACM MOBICOM*, (2003) pp. 353–367.
5. A. Høst-Madsen and J. Zhang, Capacity bounds and power allocation in wireless relay channel, IEEE Transactions on Information Theory 51(6) (2005) 2020–2040.
6. G. Kramer, M. Gastpar and P. Gupta, Cooperative strategies and capacity theorems for relay networks, to appear in *IEEE Transactions on Information Theory*, 2004. (available at http://www.eecs.berkeley.edu/ ∼ gastpar/relaynetsIT04.pdf).
7. R.U. Nabar, H. Bölcskei and F.W. Kneubühler, Fading relay channels: Performance limits and space-time signal design, IEEE Journal on Selected Areas in Communications 22(6) (2004) 1099–1109.
8. J.N. Laneman, D.N.C. Tse and G.W. Wornell, Cooperative diversity in wireless networks: Efficient protocols and outage behavior, IEEE Transactions on Information Theory 50(12) (2004) 3062–3080.
9. A. Sendonaris, E. Erkip and B. Aazhang, User cooperation diversity—Part I: System Description, IEEE Transactions on Communications 51(11) (2003) 1927–1938.
10. A. Sendonaris, E. Erkip and B. Aazhang, User cooperation diversity—Part II: Implementation aspects and performance analysis, IEEE Transactions on Communications 51(11) (2003) 1939–1948.
11. Bogdan Timus, A cost model for ad hoc extended cellular systems, in: *Proc. of the 4th Swedish Workshop on Wireless Ad-hoc Networks* (2004).
12. Pietro Lungaro, Cost/Performance Trade-offs of two layers ad hoc cellular systems, in: *Proc. of the 4th Swedish Workshop on Wireless Ad-hoc Networks* (2004).
13. Mansoor Alicherry, Randeep Bhatia and Li Li, Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks, to appear in: *Proc. of ACM MOBICOM* (2005).
14. Murali Kodialam, Thyaga Nandagopal. Routing and channel assignment for throughput maximization in multi-radio, multi-channel wireless mesh networks, to appear in: *Proceedings of ACM MOBICOM* (2005).
15. Pradeep Kyasanur and Nitin H. Vaidya, Capacity of multi-channel wireless networks: Impact of number of channels and interfaces. Technical Report in Department of Computer Science at UIUC (2005).
16. Y. Liang and V.V. Veeravalli, Gaussian orthogonal relay channel: Optimal resource allocation and capacity, submitted to IEEE Transactions on Information Theory (revised) (2005).
17. A. El Gamal and S. Zahedi, Capacity of relay channels with orthogonal components, IEEE Transactions on Information Theory to appear.
18. K. Lee and A.Yener, On Resource allocation for the multi-band relay channel in: *Proc. of 39th Annual Conference on Information Sciences and Systems* (2005).
19. M.A. Khojastepour, A. Sabharwal and B. Aazhang, On the capacity of 'Cheap' relay networks, in: *Proc. of 37th Annual Conference on Information Sciences and Systems* (2003).
20. J.N. Laneman and G.W. Wornell, Exploiting distributed spatial diversity in wireless networks, in: *Proc. of Allerton Conf. Communications, Control, and Computing* (2000).
21. P. Herhold, E. Zimmermann and G. Fettweis, A simple cooperative extension to wireless relaying, Int. Zurich Seminar on Communications (2004).
22. I. Maric and R. D. Yates, Forwarding strategy for gaussian parallel-relay networks, in: *Proc. of 38th Annual Conference on Information Sciences and Systems* (2004).
23. JaeSheung Shin, HeeSook Choi, Patrick G. Traynor and Thomas F. La Porta, Network formation schemes for multi-radio, multi-hop wireless cellular networks, *Network and security research center technical report*, TR-NAS-0005-2005, Department of Computer Science and Engineering (2005).
24. J. Proakis, *Digital Communications*, 4th ed. (New York: McGraw-Hill, 2001).
25. G. Holland and N.H. Vaidya, Analysis of TCP performance over mobile ad hoc networks, in: *Proc. of ACM MOBICOM* (1999).
26. M. Gerla, K. Tang and R. Bagrodia, TCP performance in wireless multi-hop networks, in: *Proc. of IEEE WMCSA 99* (1999).
27. K. Lee and A.Yener, On the Achievable rate of three-node cognitive hybrid wireless networks, in: *Proc. of International Conference on Wireless Networks, Communications, and Mobile Computing* (2005).

JaeSheung Shin received the B.S. and M.S. degree in Computer Science and Engineering from DongGuk University, Korea, in 1991 and 1993, respectively. He is currently working toward the Ph.D. degree in Computer Science and Engineering at the Pennsylvania State University, University Park. He is a research assistant at the Networking and Security Research Center (NSRC). Prior to joining Pennsylvania State University, he was with Electronics and Telecommunications Research Institute (ETRI), Korea, since 1993. He worked on development of 2G and 3G wireless cellular core network elements. His research interests include mobility management and signaling for wireless cellular and routing and resource allocation for multi-radio multi-hop wireless cellular networks. E-mail: jxs958@psu.edu

Kyounghwan Lee received the B.S. degree in Electrical and Electronics Engineering from University of Seoul, Seoul, Korea, in 2000, and the M.S. degree in Information and Communication Engineering from Gwangju Institute of Science and Technology, Gwangju, Korea, in 2002. He is currently a Ph.D candidate at the Electrical Engineering department at the Pennsylvania State University and a research assistant at the Wireless Communications and Networking Laboratory (WCAN@PSU). His research interests include wireless communication theory and relay networks. E-mail: kxl251@psu.edu

Aylin Yener received the B.S. degrees in Electrical and Electronics Engineering, and in Physics, from Bogazici University, Istanbul, Turkey, in 1991, and the M.S. and Ph.D. degrees in Electrical and Computer Engineering from Rutgers University, NJ, in 1994 and 2000, respectively. During her Ph.D. studies, she was with Wireless Information Network Laboratory (WINLAB) in the Department of Electrical and Computer Engineering at Rutgers University, NJ. Between fall 2000 and fall 2001, she was with the Electrical Engineering and Computer Science Department at Lehigh University, PA, where she was a P.C. Rossin assistant professor. Currently, she is with the Electrical Engineering department at the Pennsylvania State University, University Park, PA, as an assistant professor. Dr. Yener is a recipient of the NSF CAREER award in 2003. She is an associate editor of the IEEE Transactions on Wireless Communications. Dr. Yener's research interests include performance enhancement of multiuser systems, wireless communication theory and wireless networking.
E-mail:yener@ee.psu.edu

Thomas F. La Porta received his B.S.E.E. and M.S.E.E. degrees from The Cooper Union, New York, NY, and his Ph.D. degree in Electrical Engineering from Columbia University, New York, NY. He joined the Computer Science and Engineering Department at Penn State in 2002 as a Full Professor. He is the Director of the Networking Research Center at Penn State. Prior to joining Penn State, Dr. La Porta was with Bell Laboratories since 1986. He was the Director of the Mobile Networking Research Department in Bell Laboratories, Lucent Technologies. He is an IEEE Fellow and Bell Labs Fellow. Dr. La Porta was the founding Editor-in-Chief of the IEEE Transactions on Mobile Computing. He has published over 50 technical papers and holds 25 patents.
E-mail: tlp@cse.psu.edu