On-demand Diversity Wireless Relay Networks

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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. 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.

1. Introduction

In traditional wireless cellular networks, mobile nodes communicate through centralized base stations (BS) in a pre-defined spectrum. Within a cell all nodes share common spectrum. In third generation wireless systems (3G) this sharing is done via a combination of regulating power, code division multiplexing, and time division multiplexing. For example, in the 1xEV-DO system, the base station (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 the 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 throughput of 3G networks, it has been proposed that mobile nodes cooperate to form relay networks so that a BS may 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. In this way, high data rates can be achieved from the base station to the relay nodes and all users achieve higher throughput. Figure 1 shows an example in which several groups of nodes form relay networks to a base station. UCAN [4] is an example of one such system. Others have proposed relaying in a variety of networks to balance load between cells [1-3].

Whereas the UCAN system relied on a persistent 802.11 relay network, we envision a system in which the spectrum for a relay network is allocated dynamically. A wireless service provider (WSP) may "borrow" spectrum for a short time to offer a relay network when needed to overcome performance degradation. This spectrum may be broken into multiple channels so that orthogonal links and networks may be formed. Mobile nodes have agile radios which may be tuned to the proper spectrum to operate in available relay networks. As with the UCAN system, we assume that the spectrum in which the relay networks operate is not the same as the 3G interface so that there is no interference between the relay networks and the links to the BS. When network performance improves, the spectrum is reclaimed, and all nodes operate using the 3G interface once again.

In our previous work [20], five network formation schemes were investigated under a scenario in which a single frequency band was used for each relay network. Here we consider new algorithms that support the formation of relay networks that use of multiple frequencies. 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 offer non-interfering links between the mobile nodes within a single relay network so that multiple nodes within range of each 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 diverse paths between each other. Path diversity helps reduce the bit error rate, and increases 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. The destination node thus obtains two copies of the data – one from the source node and the second from the relay node. Such relay assisted schemes have been attracting much interest recently due to the performance improvement they provide [5-10].

In this paper, we consider a cross-layer approach for formation of dynamic relay networks. 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 schemes for forming relay networks in which mobile nodes communicate over multiple frequency bands and exploit two-hop diversity. We compare the five network formation schemes based on the quality of the networks that they form considering end-to-end error rate, percentage of non-interfering hops on each path, and percentage of hops with diversity on each path. One challenge in these formation algorithms is to assign frequencies to achieve as many possible non-interfering links and diversity hops as possible in the relay network. This is essentially a graph coloring problem, and is NP-hard. We show that using simple algorithms that allow local nodes to make frequency assignments based on limited information can achieve high performance gains over using networks that operate on a single frequency. Our results show that network formation algorithms that enforce some order in assigning frequencies are more effective than those that allow nodes to randomly join the relay network.

The rest of the paper is organized as follows. In section 2, we briefly discuss related work in this area. In section 3, we summarize previous work on relay network formation schemes and present the architecture and properties of dynamic multi-radio, multi-hop wireless cellular networks. These formation schemes are the basis for the new algorithms presented in section 4 which 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 two subsections we review related work on network formation and diversity in multi-hop relay networks.

2.1 Network Formation

There is a great deal of previous work on multi-hop wireless networks. Several papers address using relay networks to improve cellular network performance [1-4]. However, this work does not address the dynamic formation of relay networks. The work closest to ours addresses the formation of Bluetooth networks [11-13]. Since Bluetooth has no public broadcast channel defined, two Bluetooth devices cannot communicate with each other even when within radio range. They must thus, depending on geographical coverage, be first synchronized into piconets and then scatternets. Routing protocols can be run over the scatternet. The resulting formation algorithms are tightly coupled with special characteristics of Bluetooth networks and most research has focused only on reducing the amount of bridging overhead, the number of established Bluetooth links, and the number of piconets for minimizing inter-piconet interference.

2.2 Wireless Diversity Relay Networks

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 diverse 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]. An intense research effort is currently being directed to understanding the performance limits of such *wireless relay networks* [5-7].

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 receiver 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 [14-16], time division [5][7][8][17], or code division [9][10].

Two ways of forwarding the data at the relay are the so called amplify and forward (AF) and decode and forward (DF) schemes [8][18][19][24]. 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 [18]. 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 [18]. In order to prevent this error propagation, the relay nodes typically employ a threshold rule [18][19] by which they decide to perform DF only when the received SNRs are larger than a threshold. If the received SNR thresholds are not met, the relay nodes remain silent and the destination only listens to the direct transmission from the source. We note that DF is also more favorable than AF 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. Hence in this paper, we will consider DF scheme.

In contrast to earlier work, we will consider locating relay nodes for additional diversity in each hop of our dynamic network formation schemes. If a diversity relay node is present, it will employ an SNR threshold based decision mechanism in order to decide whether to forward the data or stay silent. Note that if the relay decides to forward the data then a new (orthogonal) frequency band will be sought to do so.

3. Summary of Previous Work on Relay Network Formation

In [20], we propose five algorithms that address the formation of relay networks that operate with a common single frequency band. The relay networks are formed dynamically when performance on the radio access network is degraded. If it is desired to establish a relay network, the available frequencies are determined (one for each relay network), and the information is broadcast over the cellular control channels so all nodes within the cell receive it simultaneously. Mobile nodes may choose to form a relay network operating on the introduced spectrum. The relay networks are formed in such a way that each node receives data from the previous hop *once*, i.e. diversity through combining multiple copies is not present.

Figure 1 shows an example of relay network formation. In this example, two relay networks operating on different frequencies are formed in the cell. This requires that each node be equipped with an agile radio so that it may dynamically change frequencies and communication formats to be most suitable based on availability, interference level, or business arrangement [21, 22].

Relay network formation occurs in two phases: the gateway (GW) discovery phase and the path setup phase. In the GW discovery phase, gateway nodes are chosen for each group. 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 figure 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 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 base station with its neighbor's. If the node has the best signal compared to all neighbors, the node acts as a GW node.

In the path setup phase, 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 base station. 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. When a node having a forward path to the BS receives a *RREQ*, it returns a route reply (*RREP)* message to the source node immediately. Moreover, if a node passively learns a route to the BS, i.e., it already has a forwarding path to the BS, it does not launch its own route discovery.

In [20], we describe five network formation algorithms. Each formation scheme defines the order in which nodes initiate a route discovery to the BS. We include No Wait (NW – all nodes attempt to find paths immediately), Furthest First (FF), Nearest First (NF), Locally Furthest one First (LFF – furthest node within a group launches a *RREQ* first), and Region-based LFF (R-LFF).

Besides NW, all of the methods use some node ordering to leverage passive route learning 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.

In FF, nodes the furthest from the base station launch *RREQ*s first, so that all nodes on the path between this node and the base station will passively learn a route. When a node already having a path to the BS receives a *RREQ*, it returns *RREP* to the source node immediately; thus another way to reduce control overhead is to let the node nearest to the BS start the route discovery first (NF). 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.

Even though LFF can reduce the formation latency through parallelism, it 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. Figure 2 shows an example of each formation algorithm.

We evaluate these algorithms in terms of latency, signaling traffic, and load at the gateway nodes. From the evaluation, we found that the three schemes, FF, LFF, and R-LFF, in which the furthest nodes launch *RREQ*s first perform best generally.

4. Network Formation via Diversity

The network formation algorithms presented in Section 3 were designed to support relay networks operating in a single frequency. In this section we present several network formation schemes to support relay networks comprised of multiple frequencies. These new formation algorithms are based on those described in section 3, with two significant extensions. The first extension assigns frequencies so that each link in the relay network is orthogonal, if possible. The second extension adds 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 Figure 3. Mobile nodes cooperate to form a relay path to a BS through a GW node. Nodes may play a combination of three roles. ***Source*** nodes generate traffic. ***Intermediate*** nodes forward traffic on the path from the source to the GW. ***Relay*** nodes provide a diversity path between two nodes with a direct link. Nodes may play all of these roles simultaneously. In Figure 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 diversity to the link between nodes 2 and 3; it is 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 is used to advertise the frequencies available in a relay network.
- Mobile nodes that join the relay networks 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 a data at a time, i.e., each node does not transmit a 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 as shown in Figure 3. In Figure 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. We limit the diversity to single hop between adjacent nodes.

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

4.1. Gateway Discovery and SNR Measurement

During network formation each node attempts to select the best frequency and add diversity to each link it terminates on a path. Before choosing a frequency or deciding if diversity should be added, each node calculates the local error probability given its local measured SNRs from its neighbors. We describe the procedures for learning these SNRs below.

Every node joining the relay network initially broadcasts a *NADV* message as part of the GW discovery phase. The *NADV* messages are broadcast over all available frequencies in the relay network. Thus, each node receives *NADV* messages from its neighbors over all frequencies and can measure the SNR value of all received signals. In order to avoid severe collisions during this procedure, each node waits for a random time before transmitting the *NADV*.

Figure 4 shows the example of the SNR measurement in each node. In this example, the BS advertises 3 frequencies for a relay network. Nodes 1, 2, and 3 are willing to join the relay network. Each node broadcasts *NADV* messages over all frequencies after receiving the advertisement from the BS. Because these three nodes are reachable from each other, they can each measure the received SNR from each neighbor on each frequency. The resulting neighbor table for Node 1 is shown in Figure 4. For each neighbor the table contains the ID of the node, its received signal quality from the BS, and the received SNR of the node on each frequency. Based on the received signal quality from the BS for each node, the GW node is chosen.

4.2. Path Setup

In the path setup phase, the nodes join the relay network by forming a path through one of the gateways to the base station. We use a modified version of AODV as the protocol to find this path. As shown in figure 5, the *RREQ* message contains the SNR information as well as the path information of the previous node on the forward path. The *RREP* message contains the frequency information assigned by the previous node on the reverse path.

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 6 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 node 1, 3, 6, and 7. Since there are multiple paths from node 1 to 6 and from node 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 *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 next node on the reverse path and the *RREP* contains the frequencies by the previous 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 7 shows the frequency assignment algorithm and an example of the frequency assignment at node 7 in figure 6. 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 sent from node 6 and the GW in its neighbor table. When node 1 sends out a *RREQ*, node 7 receives the *RREQ* from node 6 and stores the path information and SNR information of the *RREQ* in its routing 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 *RREP* has no available 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 consist of a direct link and one relay node. In figure 6, we have two alternative paths: one from node 1 to 6 and the other from node 3 to 6. Since the alternative path from node 1 to 6 has more than one relay node, it is not used for a diverse path. As a result, we have only one candidate for adding diversity from node 3 to node 6.

As shown in figure 8, 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 figure 8, 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. Even if it receives another duplicate of *RREQ* from node 5, it is not sent through two-hop diverse path. Thus it is ignored.

4.2.3. Diversity Setup

If the joint node detects a two-hop diverse path as described above, it attempts to add a diversity path. Setting up the diversity path includes checking if there are available frequencies above the SNR threshold to be assigned to the diverse path, 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, over the available frequencies. 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_{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.

Figure 9 shows the diversity setup algorithm and an example. As shown in figure 9, node 6 reselects the up and downlink frequency, f_u and f_d, between node 3 and itself, and then it selects suitable up and downlink frequencies, f_{u_relay} and f_{d_relay}, for the relay node based on the information in its routing table and neighbor table.

4.3. Adding diversity to the relay node

Relay nodes may act as a source node as well as shown in Figure 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 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 add diversity to the relay node, the joint node assigns up and downlink frequencies and establishes diversity in the same way described in the previous section. This phase is logically separated from the path setup phase. However, the joint node can be performed all procedures in this phase simultaneously when 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, we discuss the resulting performance improvement in section 7.

5. Error Probability of 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 single-hop three node relay network as shown in Figure 10. We assume that binary phase-shift keying (BPSK) is employed at each node along with the optimum detection schemes, i.e, the maximum-likelihood (ML) detection at the relay and the maximum–ratio combining (MRC) at the destination [23]. We assume that our channels are quasi-static. We also assume that the noise, Z_{sd}, Z_{sr}, Z_{rd}, are identically independent Additive White Gaussian Noise (AWGN) with zero-mean and unit variance. The input-output signal model is given by

$$Y_{rd} = h_{rd}\tilde{b} + Z_{rd} \tag{1}$$

$$Y_{sd} = h_{sd}b + Z_{sd} \tag{2}$$

$$\tilde{Y}_{sr} = h_{sr}b + Z_{sr} \tag{3}$$

Let b denote the transmitted bit from the source that is either 1 or -1 of the random variable for BPSK transmission. $\tilde{b}$ is the transmitted bit from the relay that is either b or $-b$ depending on the correctness of decision at the relay. 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}. We then have the received SNR at the each node given by

$$\gamma_{sr} = \left|h_{sr}\right|^2, \qquad \gamma_{sd} = \left|h_{sd}\right|^2, \qquad \gamma_{rd} = \left|h_{rd}\right|^2 \tag{4}$$

If we consider the possibility of the decoding error at the relay, the error probability is given by

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

where γ_{th} is the received SNR threshold at the relay for initiating DF operation. The error probability of BPSK is expressed as $Q\left(\sqrt{2SNR}\right)$ where $Q(x)$ function is defined by [23]

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

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

$$P^d_{c|\gamma_{sr} \geq \gamma_{th}} = P^r_c P^d_{c|correct\,at\,relay} + P^r_e P^d_{c|error\,at\,relay} \tag{7}$$

where P^r_c is the correct decision probability at the relay, $P^d_{c|correct\,at\,relay}$ 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 $P^d_{c|error\,at\,relay}$ 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

$$\begin{aligned} P^r_c &= 1 - Q\left(\sqrt{2\gamma_{sr}}\right) \\ P^r_e &= Q\left(\sqrt{2\gamma_{sr}}\right) \\ P^d_{c|correct\,at\,relay} &= 1 - Q\left(\sqrt{2\left(\gamma_{sr} + \gamma_{sd}\right)}\right) \end{aligned} \tag{8}$$

where $P^d_{c|correct\,at\,relay}$ is the correct probability of MRC detection for receiving two identical signals from two diversity paths [23].

Next, we set out to find $P^d_{c|error\,at\,relay}$. If there is an error in 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

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

where W_{rd} is the weight for Y_{rd} and W_{sd} is the weight for Y_{sd}. The superscript * stands for complex conjugate. Thus, the output signal of the MRC is given by

$$U = \frac{-h_{rd}^2 + h_{sd}^2}{\sqrt{h_{rd}^2 + h_{sd}^2}} X + \frac{h_{rd}^*}{\sqrt{h_{rd}^2 + h_{sd}^2}} Z_{rd} + \frac{h_{sd}^*}{\sqrt{h_{rd}^2 + h_{sd}^2}} Z_{sd} \tag{11}$$

The output signal, U can be written as

$$U = \alpha X + Noise \tag{12}$$

Depending on the sign of α, two cases occur at the destination.

Case 1: If $\alpha > 0$, the noise power should not exceed the signal power for a correct decision at the destination and the correct decision probability is denoted as $P_{c|error\,at\,relay\,and\,\alpha>0}^{d}$

Case 2: If $\alpha < 0$, the noise power should be larger than the signal power for reversing the sign of the signal at the destination and the correct decision probability is denoted as $P_{c|error\,at\,relay\,and\,\alpha<0}^{d}$.

Then, $P_{c|error\,at\,relay}^{d}$ is given by

$$P_{c|error\,at\,relay}^{d} = \begin{cases} 1 - Q\left(\sqrt{2\gamma_{com}}\right) & if\ \gamma_{sd} \geq \gamma_{rd} \\ Q\left(\sqrt{2\gamma_{com}}\right) & if\ \gamma_{sd} < \gamma_{rd} \end{cases} \tag{13}$$

where $P_{c|error\,at\,relay}^{d}$ for $\gamma_{sd} \geq \gamma_{rd}$ corresponds to $P_{c|error\,at\,relay\,and\,\alpha>0}^{d}$ and $P_{c|error\,at\,relay}^{d}$ for $\gamma_{sd} < \gamma_{rd}$ corresponds to $P_{c|error\,at\,relay\,and\,\alpha<0}^{d}$. γ_{com} is the combined SNR at the MRC given by

$$\gamma_{com} = \frac{\left(-\gamma_{rd} + \gamma_{sd}\right)^2}{\gamma_{rd} + \gamma_{sd}} \tag{14}$$

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

$$P_{c|\gamma_{sr} \geq \gamma_{\text{th}}}^{d} = \begin{cases} \left(1 - Q\left(\sqrt{2\gamma_{sr}}\right)\right)\left(1 - Q\left(\sqrt{2\left(\gamma_{sd} + \gamma_{rd}\right)}\right)\right) + Q\left(\sqrt{2\gamma_{sr}}\right)\left(1 - Q\left(\sqrt{2\gamma_{com}}\right)\right) & if\ \gamma_{sd} \geq \gamma_{rd} \\ \left(1 - Q\left(\sqrt{2\gamma_{sr}}\right)\right)\left(1 - Q\left(\sqrt{2\left(\gamma_{sd} + \gamma_{rd}\right)}\right)\right) + Q\left(\sqrt{2\gamma_{sr}}\right) Q\left(\sqrt{2\gamma_{com}}\right) & if\ \gamma_{sd} < \gamma_{rd} \end{cases} \tag{15}$$

Finally, the error probability is obtained by inserting (15) 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 is expressed as

$$P_{e2e} = 1 - \prod_{i=1}^{N}\left(1 - P_{e,i}\right) \tag{16}$$

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 (16), 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. For clarity of exposition, we will use this upper bound for the end-to-end error rate.

To justify using the diversity relay channel, we consider the example with three hops shown in Figure 11. We compare the bit error probabilities of direct transmission only, versus transmission using diversity relay nodes in Figure 12. We assume that the received SNR threshold at each relay node is 10dB. For the diversity case, the received SNR at each hop is 10dB, 10dB, and 15dB, 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, especially when direct link is relatively good. This is because the relay with a poor link can cause error propagation. This is demonstrated in Figure 13. 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 higher error in detection at the relay and we have a better relay to the destination channel, the destination is more likely to receive the erroneous bit. However, if the relay to the destination channel is bad, the erroneous bit can be flipped back to original correct bit. Thus, when there is high detection error at the relay, we can get better probability of error as the relay to the destination link gets worse. However, when there is smaller error at the relay, better relay to the destination link will provide better error probability. Based on this observation, we conclude that the received SNR threshold has to be set to make sure that there is low error probability at the relay. Throughout our simulations, we use 10dB as the received SNR threshold which corresponds to a decoding error of 10^{-6} at the relay node.

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 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 $886 \times 886\,\mathrm{m}^2$. 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 seconds 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 interfering 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 is the average of error probability of all source and destination pairs in the network. The average end-to-end error probability, $P_{ava.e2e}$, is given by

$$P_{avg.e2e} = \frac{\sum_{i=1}^{S} P_{e2e,i}}{S} \tag{17}$$

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 *i*th 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, is will choose a frequency that is already assigned to another node. From an error probability point of view this interfering link does not have any impact because we assume that a MAC protocol resolves contention. However, it has an impact on the end-to-end transmission delay of the network. 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.

Percentage of hops with interfering links =

$$\frac{\sum_{i=1}^{S} \frac{\#\ of\ hops\ with\ interfering\ links\ of\ the\ path\ from\ node\ i\ to\ a\ GW\ node}{total\ \#\ of\ hops\ of\ the\ path\ from\ node\ i\ to\ a\ GW\ node}}{S} \tag{18}$$

If a joint node detects a two-hop diverse path, it will select a frequency to provide diversity if one is available that has a received SNR above the SNR threshold. Otherwise, it fails to form a diversity link. 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.

$$Relative\ diversity\ percentage = \frac{\sum_{i=1}^{S} \frac{\#\ of\ hops\ with\ actual\ diversity\ of\ the\ path\ from\ node\ i\ to\ a\ GW\ node}{\#\ of\ hops\ with\ all\ possible\ diversity\ of\ the\ path\ from\ node\ i\ to\ a\ GW\ node}}{S} \tag{19}$$

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.

$$Absolute\ diversity\ percentage = \frac{\sum_{i=1}^{S} \frac{\#\ of\ hops\ with\ actual\ diversity\ of\ the\ path\ from\ node\ i\ to\ a\ GW\ node}{total\ \#\ of\ hops\ of\ the\ path\ from\ node\ i\ to\ a\ GW\ node}}{S} \tag{20}$$

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 0dB and 20dB.

As shown in figure 14, in order to form a diversity hop without any interfering links, each node should have at least 6 available frequencies for uplink and downlink transmission. Thus, if 12 frequencies are available in a relay network, each joint node can form a diversity hop for both uplink and downlink flows to one neighbor.

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.

6.3.1. Scenario I

Figure 15a shows the average end-to-end error probability of each node in the case in which no diversity is added to a path. Given the 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 15b shows the average number of hops on the path from each node to the GW for each algorithm. Due to the characteristics of NF, each path has a relatively the large number of hops so it will tend to have higher error rates.

Figure 16 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. Figures 17-21 show how varying the number of frequencies available in the relay network affects the different algorithms. They show the average end-to-end error probability for each node as the number of frequencies available in the relay network varies from 8 to 12. These figures show that even if we reduce the number of available frequencies in a relay network to 8, the average error probability of the FF-based algorithms and NF do not change much, because, in these schemes, joint nodes still have enough frequencies to achieve almost 100% diversity. NW is affected most by the reduction in frequencies because it does not allocate the frequencies efficiently and achieves low diversity.

In these figures, 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 Figures 22-23. Figure 22 shows the relative diversity percentage on the path from each node to the GW node. Figure 23 shows the absolute diversity percentage for the same scenarios.

As shown in Figures 22 and 23, 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 Figure 15b. 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 Figures

22 and 23, 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 figures 22 and 23, 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 Figure 22, 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.

Figure 24 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 –12 frequencies and random received SNR [0 .. 20dB]

Figure 25 shows the average end-to-end error probability of each node when diversity is included in the path setup. In this case, every node has a random SNR value in the range of [0 .. 20dB]. 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.

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 figure 16. NF generally has 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.

Figure 26 shows the improvement in end-to-end error probability by adding diversity to the relay node. In this figure, we observe that FF, LFF, and R-LFF algorithms which let the nodes furthest from the BS start the route discovery first have better improvement compared to other schemes. In these schemes, if the furthest node initiates the route discovery, many relay nodes connected to the joint nodes on the direct path will passively learn the route. Thus, adding diversity these relay nodes result in much better performance. As shown in figure 22, NF tends to have small number of diversity hops. In NW, all nodes start the routing discovery simultaneously. Thus, even if diversity is not additionally established, the relay nodes have a greater possibility to have their own diverse path compared to other schemes.

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.

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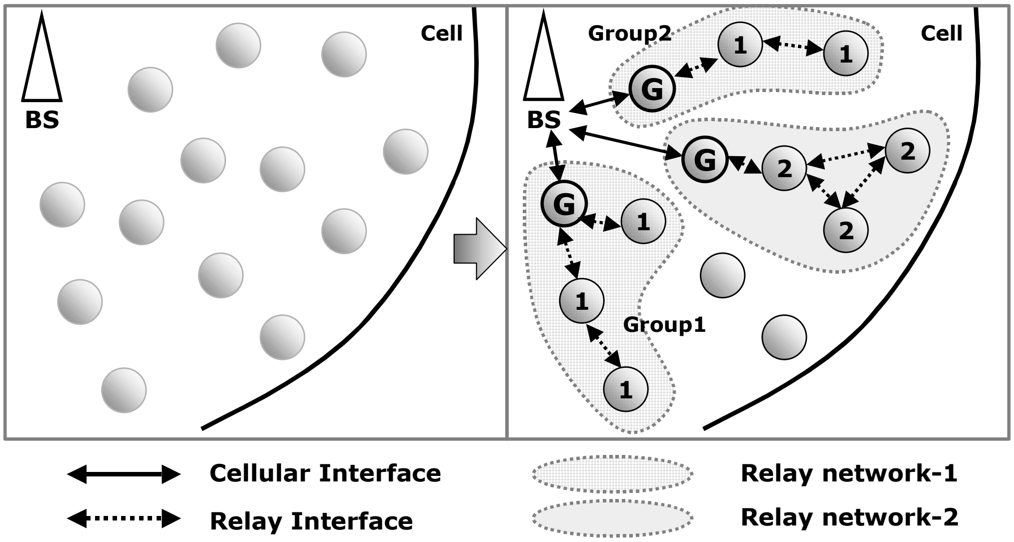
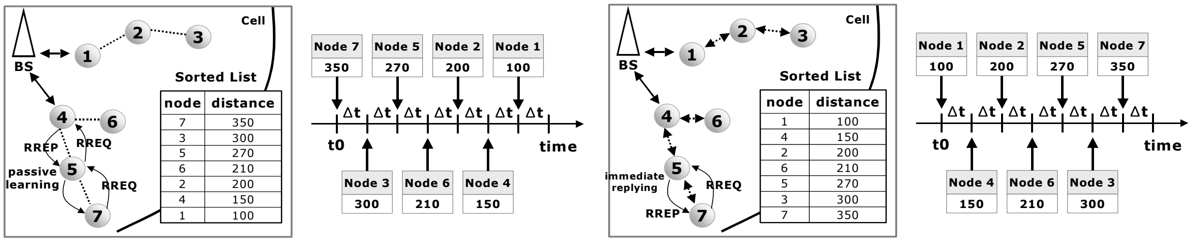
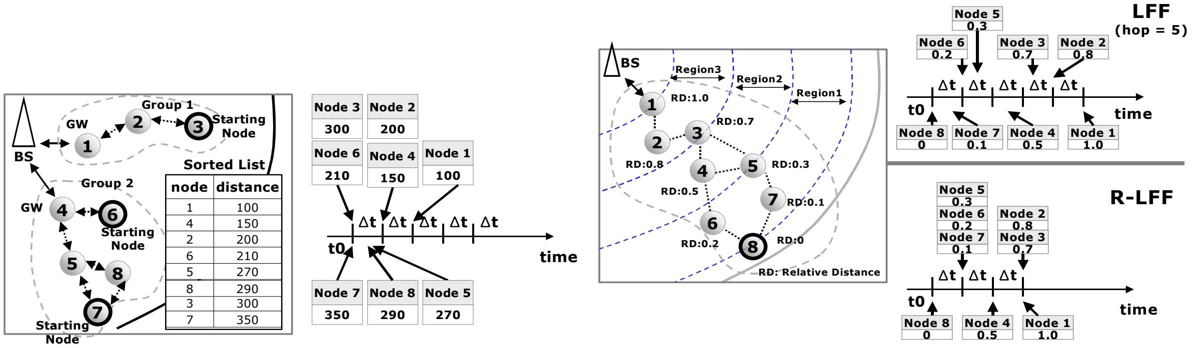


Figure 1. Example of relay network formation



FF Scheme

NF Scheme



LFF Scheme

R-LFF Scheme

Figure 2. Example of formation schemes

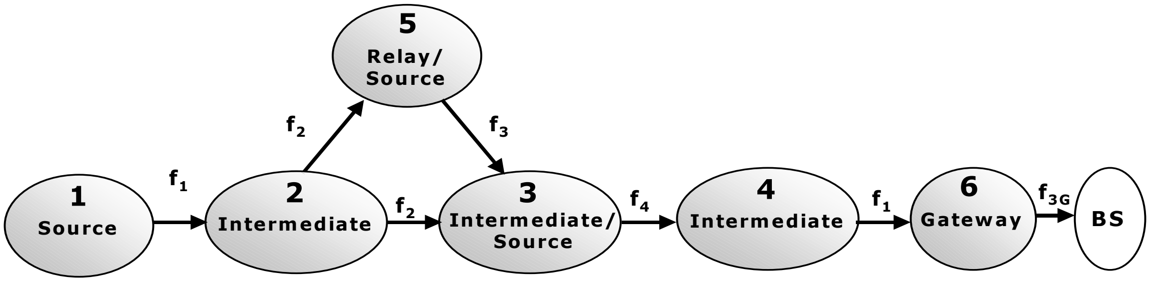
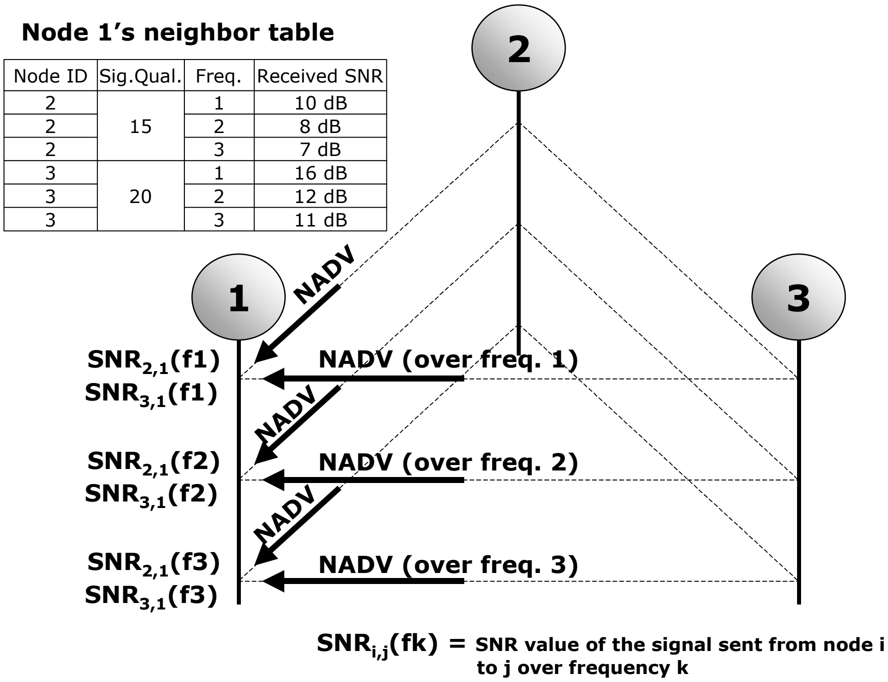


Figure 3. Network Model



Node 1's neighbor table

Node ID	Sig.Qual.	Freq.	Received SNR
2	15	1	10 dB
2		2	8 dB
2		3	7 dB
3	20	1	16 dB
3		2	12 dB
3		3	11 dB

$SNR_{i,j}(fk)$ = SNR value of the signal sent from node i to j over frequency k

Figure 4. Example of SNR measurement

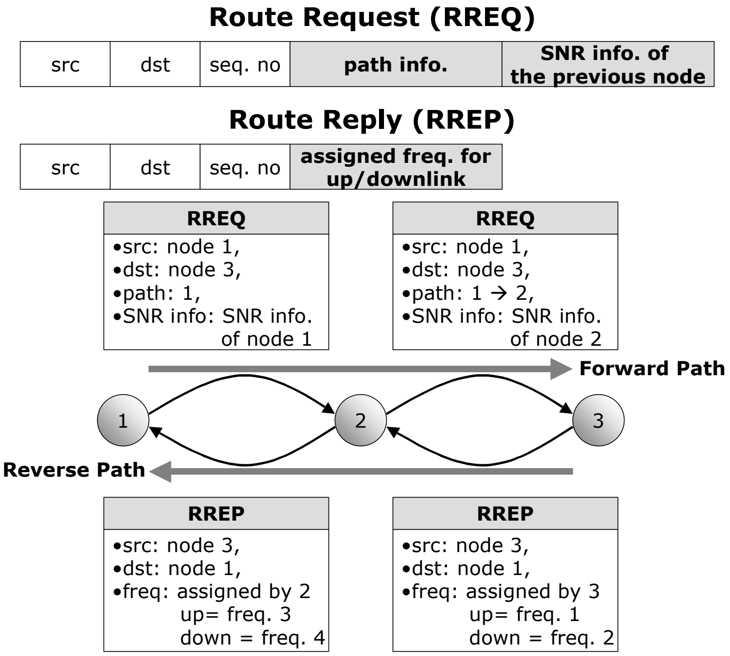


Figure 5. Main components of the routing messages

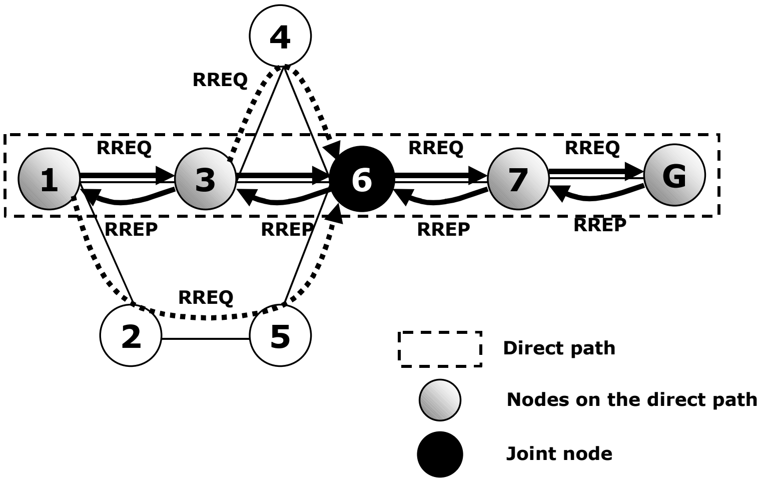
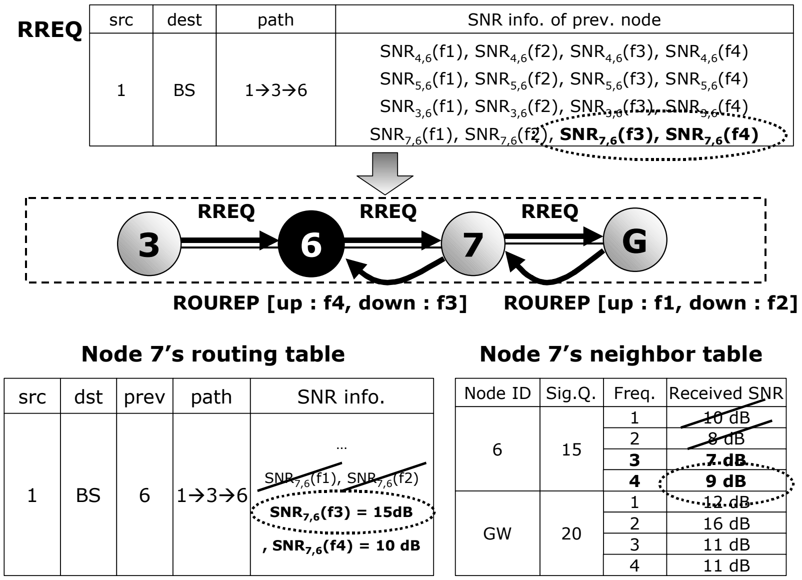


Figure 6. Example of the direct path and joint node

```
Freq_assignment( ) {
    i = ID of current node ;
    j = ID of the next node on the reverse path ;
    current_AF_i = { set of available frequencies of node i } – { assigned frequencies by the previous
        node on the reverse path };
    picking up a frequency for downlink,
        fd = {fd | max. $SNR_{i,j}$( fd ), for fd $\in$ current_AF_i };
    picking up a frequency for uplink,
        fu = {fu | max. $SNR_{j,i}$( fu ), for fu $\in$ (current_AF_i – {fd} ) };
    , where $SNR_{j,i}$( fk ) = SNR value of the signal sent from node j to i over frequency fk
}
```



RREQ

src	dest	path	SNR info. of prev. node
1	BS	1→3→6	$SNR_{4,6}$(f1), $SNR_{4,6}$(f2), $SNR_{4,6}$(f3), $SNR_{4,6}$(f4) $SNR_{5,6}$(f1), $SNR_{5,6}$(f2), $SNR_{5,6}$(f3), $SNR_{5,6}$(f4) $SNR_{3,6}$(f1), $SNR_{3,6}$(f2), $SNR_{3,6}$(f3), $SNR_{3,6}$(f4) $SNR_{7,6}$(f1), $SNR_{7,6}$(f2), **$SNR_{7,6}$(f3), $SNR_{7,6}$(f4)**

Node 7’s routing table

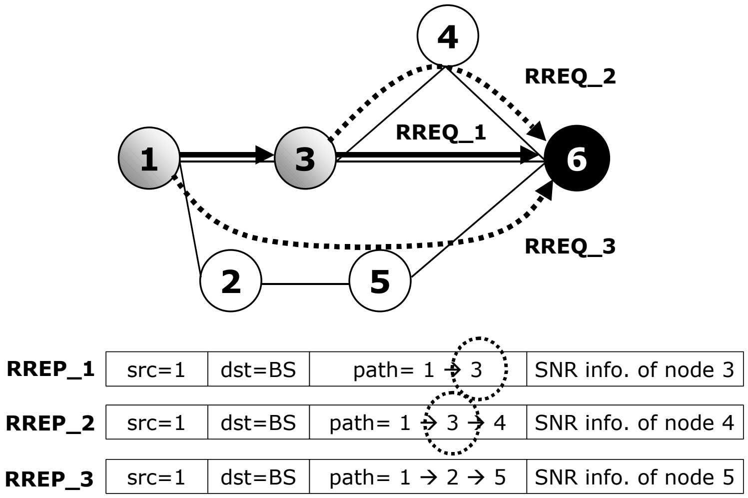
src	dst	prev	path	SNR info.
1	BS	6	1→3→6	… ~~$SNR_{7,6}$(f1)~~, ~~$SNR_{7,6}$(f2)~~ **$SNR_{7,6}$(f3) = 15dB** **, $SNR_{7,6}$(f4) = 10 dB**

Node 7’s neighbor table

Node ID	Sig.Q.	Freq.	Received SNR
6	15	1	~~10 dB~~
		2	~~8 dB~~
		3	**7 dB**
		4	**9 dB**
GW	20	1	12 dB
		2	16 dB
		3	11 dB
		4	11 dB

Figure 7. Frequency assignment

```
Detect_two_hop_diverse_path( ) {
    for (all received RREQs) {
        prev( j ) = the previous node ID of received RREQ j ;
        for ( all received RREQ k except RREQ j ) {
            if( path_info [last – 1] of RREQ k == prev( j ) )
                relay node = path_info [last];
                return true;
        }
    }
    return false;
}
```



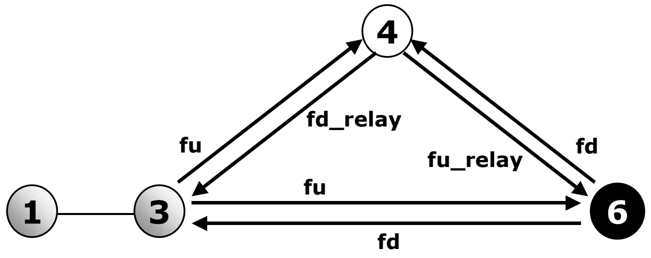
RREP_1	src=1	dst=BS	path= 1 → 3	SNR info. of node 3
RREP_2	src=1	dst=BS	path= 1 → 3 → 4	SNR info. of node 4
RREP_3	src=1	dst=BS	path= 1 → 2 → 5	SNR info. of node 5

Figure 8. Example of detecting two-hop diverse path

```
Diversity_setup( ) {
    i = ID of current node ;
    j = ID of the next node on the reverse path ;
    if( Detect_two_hop_diverse_path( ) ) {
        relay = ID of relay node of the diverse path ;

        // Reselect fu and fd
        fu = {fu | max. $SNR_{j\,,\,relay}$( fu ) instead of max. $SNR_{j\,,\,i}$( fu ), for fu $\in$ current_AF_i };
        fd = {fd | max. $SNR_{i\,,\,relay}$( fd ) instead of max. $SNR_{i\,,\,j}$( fu ), for fd $\in$ current_AF_i };

        // Frequency assignment for the diverse path
        if( $SNR_{j,relay}$ (fu) > SNR_threshold ) {
            // Setting up the diverse path; picking up additional frequencies for relay node
            new_AF_i = current_AF_i – { fu, fd };
            pick up a frequency for uplink through the relay,
                fu_relay = {fu_relay | max. $SNR_{relay\,,\,i}$( fu_relay ), for fu_relay $\in$ new_AF_i };
            pick up a frequency for uplink,
                fd_relay = {fd_relay | max. $SNR_{relay\,,\,j}$ ( fd_relay ), for fd_relay $\in$ (new_AF_i –
              {fu_relay} ) };
        }
}
```



Node 6’s routing table

src	dst	prev	path	SNR info. of prev. node
1	BS	3	1 → **3**	$SNR_{1,3}$(f1), $SNR_{1,3}$(f2), …, $SNR_{1,3}$(fk) **$SNR_{4,3}$(f1), $SNR_{4,3}$(f2), …, $SNR_{4,3}$(fk)** $SNR_{6,3}$(f1), $SNR_{6,3}$(f2), …, $SNR_{6,3}$(fk)
		4	1 → **3** → 4	**$SNR_{3,4}$(f1), $SNR_{3,4}$(f2), …, $SNR_{3,4}$(fk)** **$SNR_{6,4}$(f1), $SNR_{6,4}$(f2), …, $SNR_{6,4}$(fk)**
		5	1 → 2 → 5	$SNR_{2,5}$(f1), $SNR_{2,5}$(f2), $SNR_{2,5}$(f3), $SNR_{2,5}$(fk) $SNR_{6,5}$(f1), $SNR_{6,5}$(f2), $SNR_{6,5}$(f3), $SNR_{6,5}$(fk)

Node 6’s neighbor table

Node ID	Dist.	Freq.	Received SNR	Node ID	Dist.	Freq.	Received SNR
4	**20**	**1**	**10 dB**	5	19	1	10 dB
		2	**8 dB**			2	8 dB
		..	**…**			..	…
		k	**9 dB**			k	9 dB
3	10	1	12 dB	7	15	1	12 dB
		2	16 dB			2	16 dB
		..	…			..	…
		k	11 dB			k	11 dB

Figure 9. Diversity setup

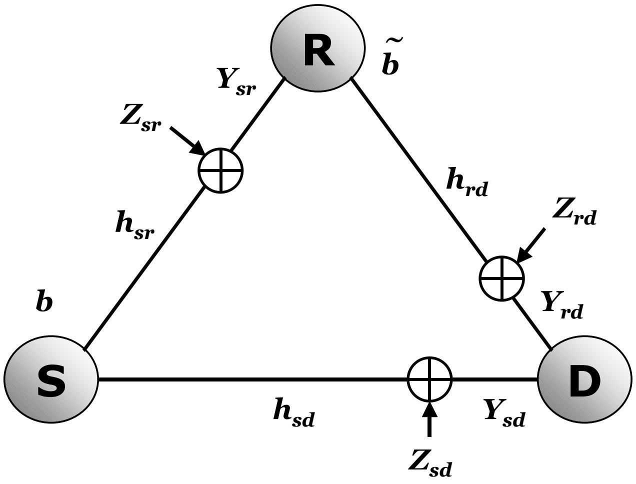


Figure 10: Single-hop three nodes relay network

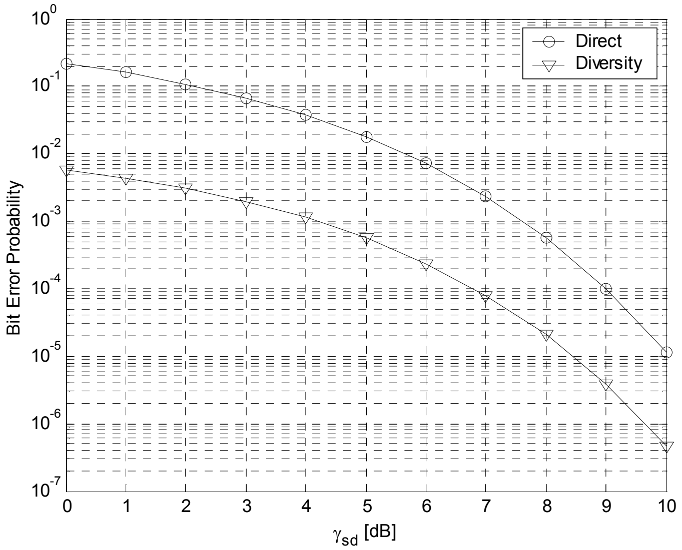


Figure 11: Bit error probability of two schemes when the received SNR threshold is 10dB

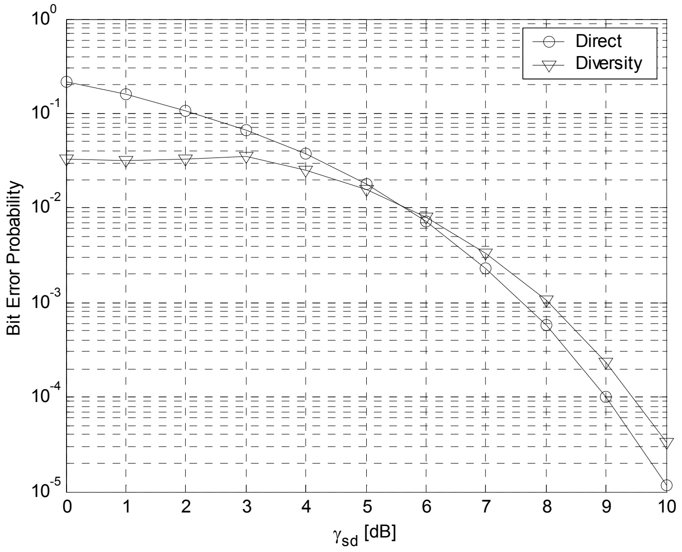


Figure 12: Bit error probability of two schemes when the received SNR threshold is 3dB

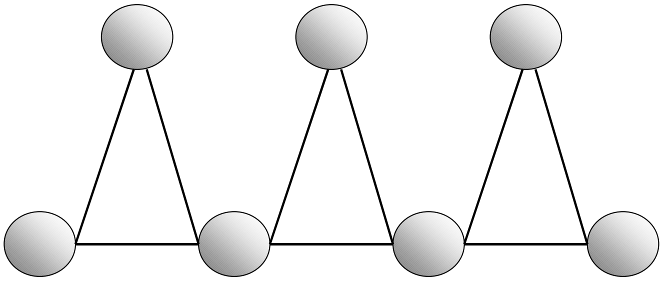


Figure 13: Three-hop relay network

Simulation time	30 seconds
# of mobile nodes in a cell	Varying from 10 to 80 nodes
Packet size	1500 bytes
Routing protocol	Modified AODV
MAC for control signal	IEEE 802.11 b
Transmission range of control signal	115m
# of frequencies available within a relay network	Varying from 8 to 12 frequencies

Table 1. Simulation Parameters

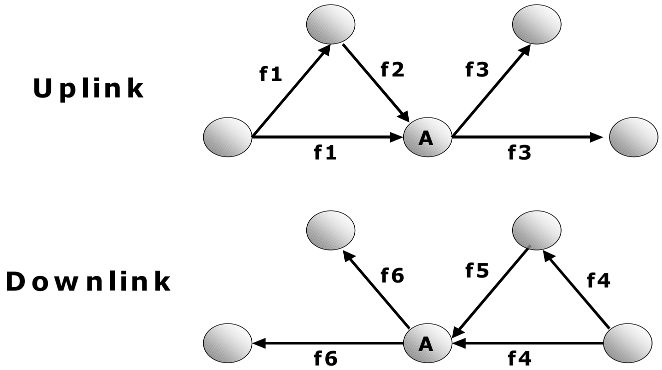
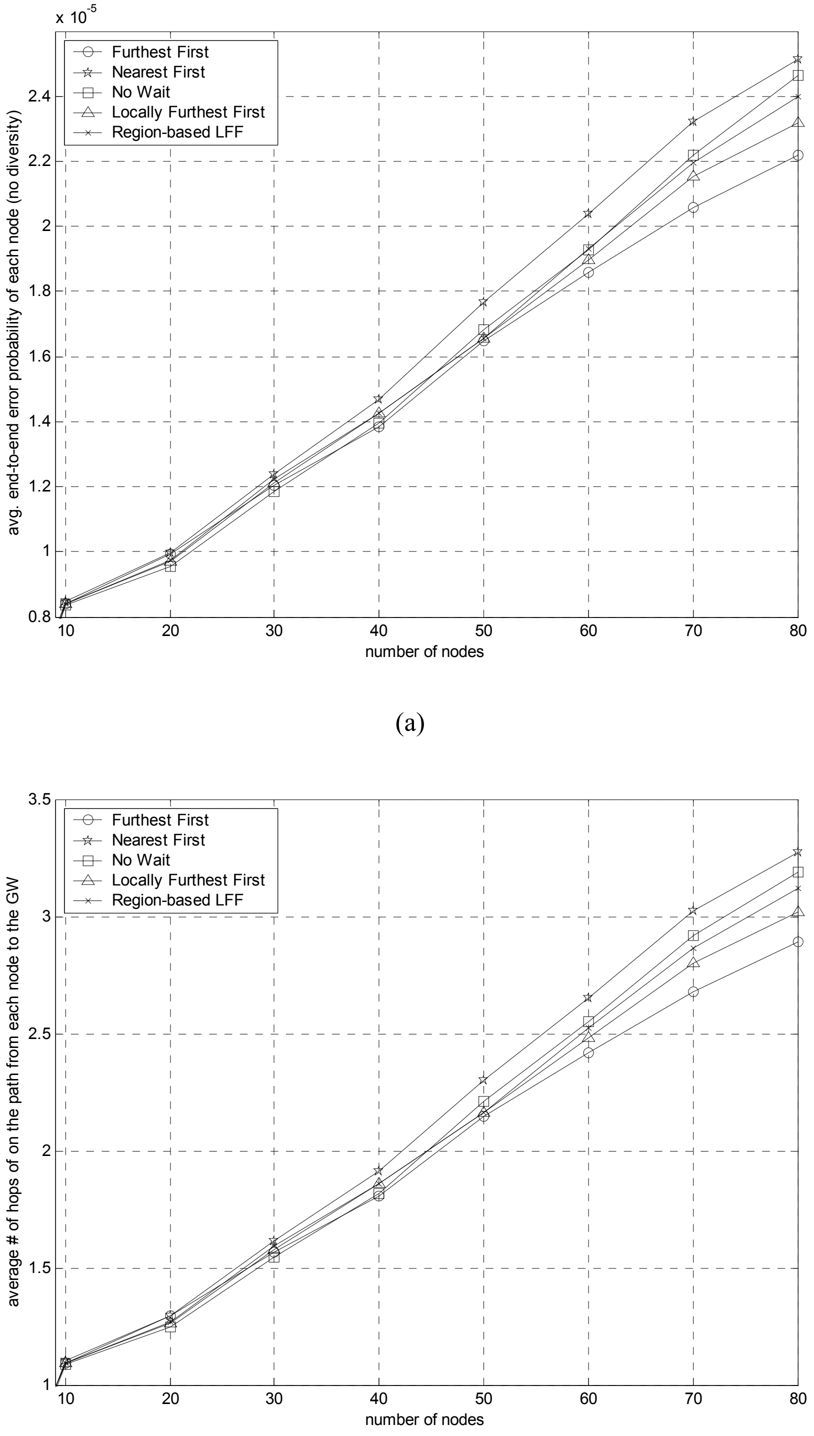


Figure 14. The number of frequencies required for diversity



(a)

(b)

Figure 15. (a) Average end-to-end error probability of each node (no diversity), (b) average number of hops of each path

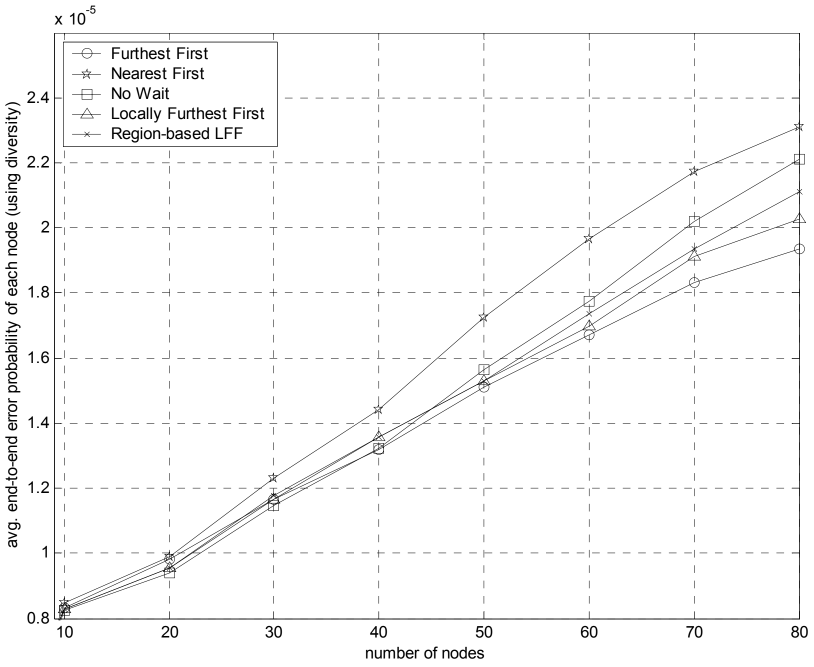


Figure 16. Average end-to-end error probability of each node (with diversity)

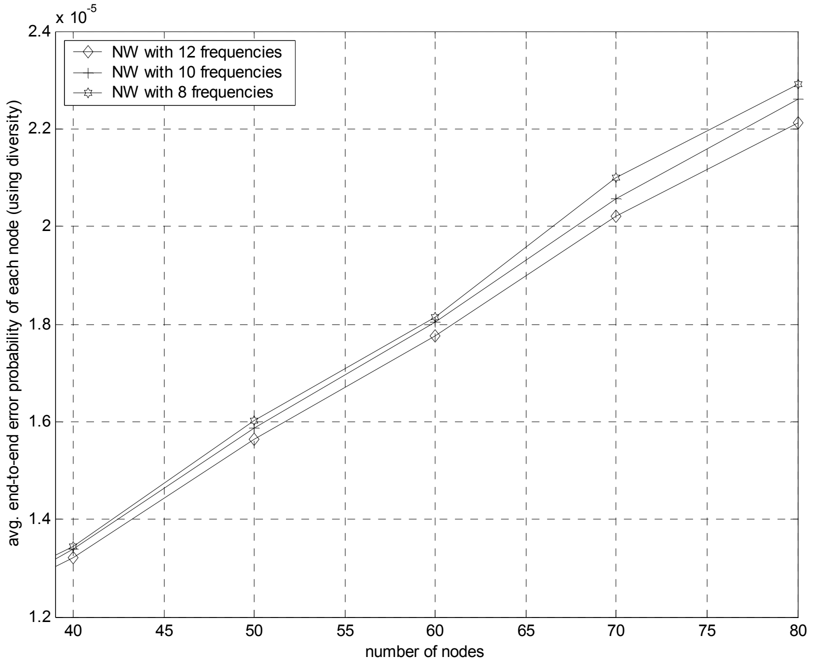


Figure 17. Average end-to-end error probability of NW scheme using diversity with various frequencies

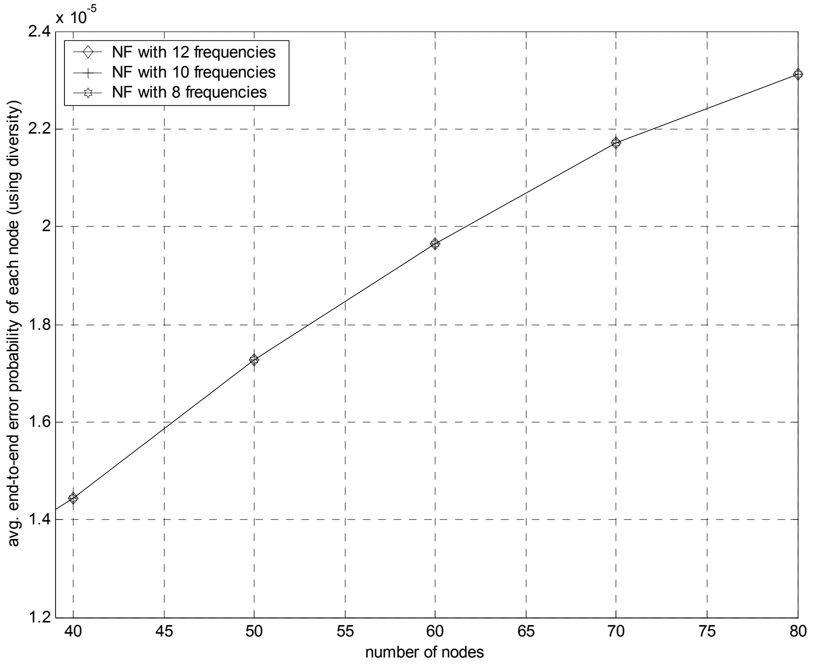


Figure 18. Average end-to-end error probability of NF scheme using diversity with various frequencies

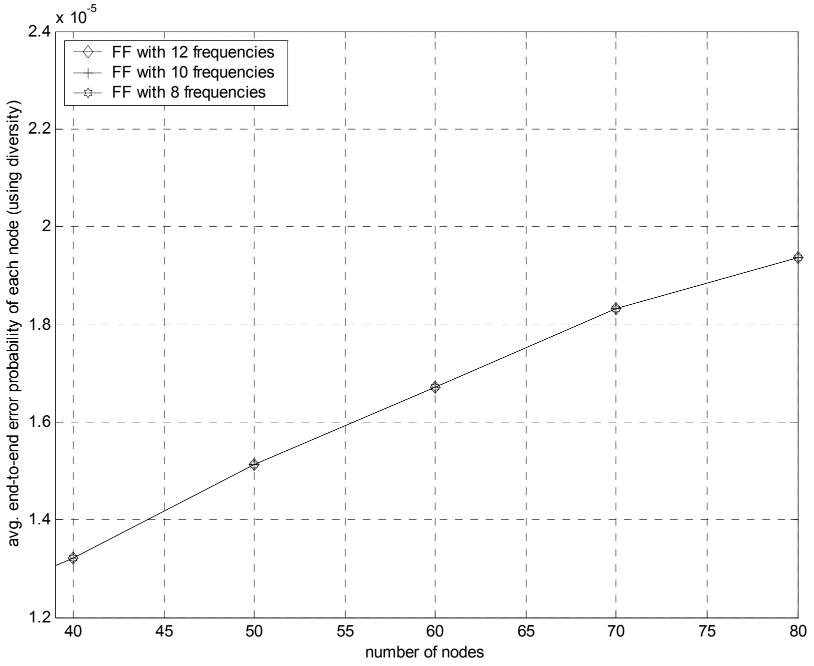


Figure 19. Average end-to-end error probability of FF scheme using diversity with various frequencies

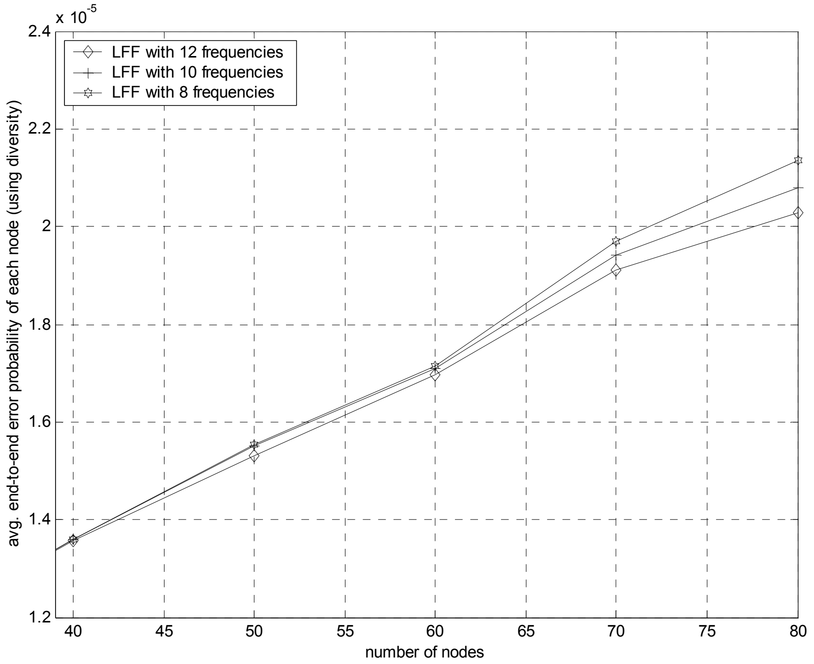


Figure 20. Average end-to-end error probability of LFF scheme using diversity with various frequencies

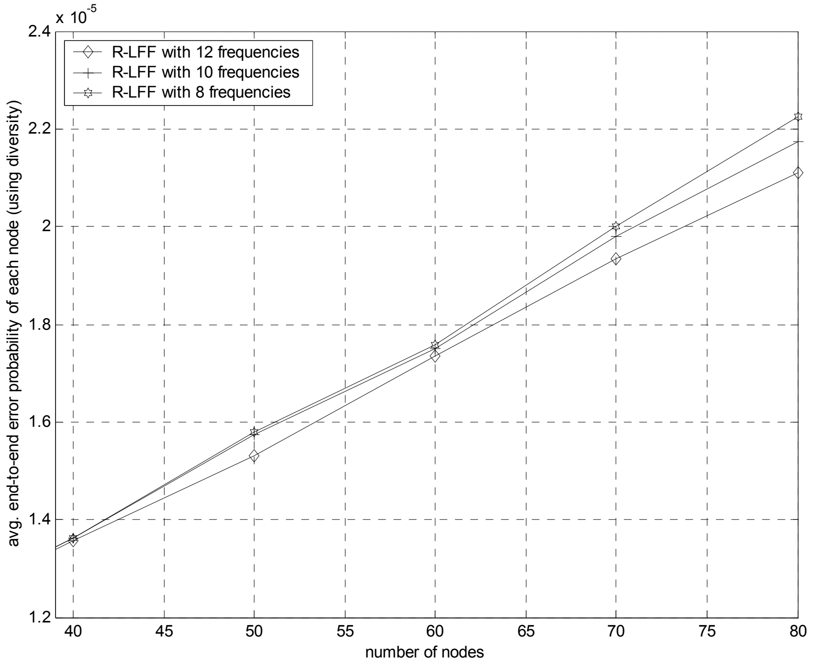
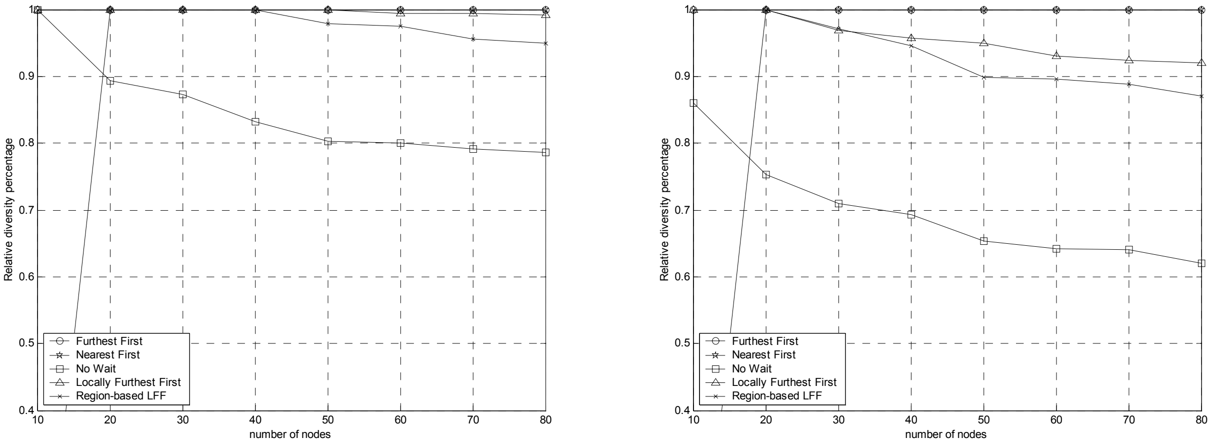
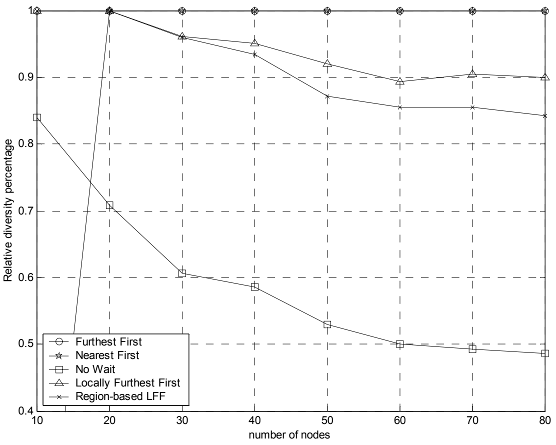


Figure 21. Average end-to-end error probability of R-LFF scheme using diversity with various frequencies



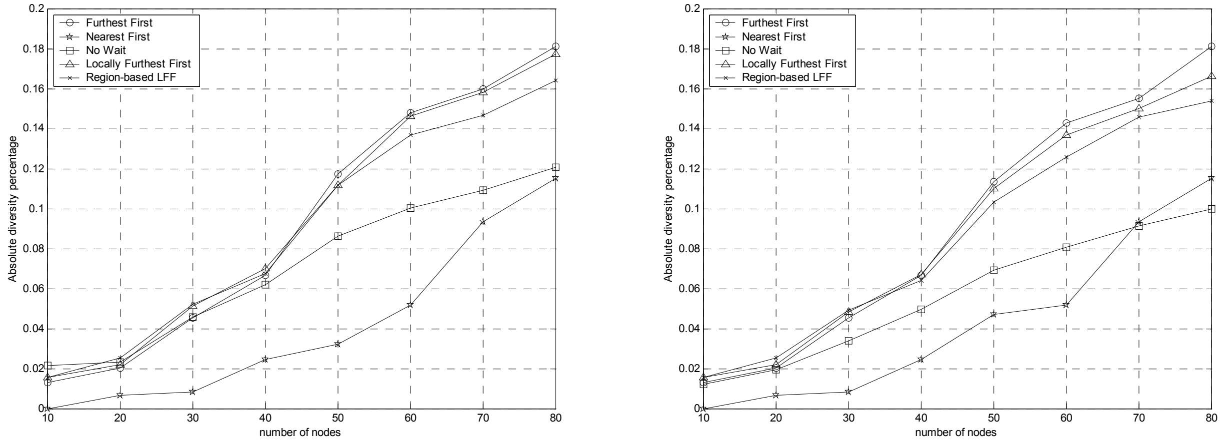
Number of frequency = 12

Number of frequency = 10



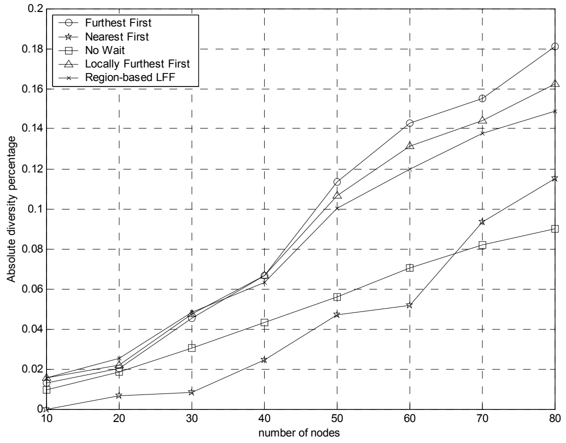
Number of frequency = 8

Figure 22. Relative diversity percentage on the path



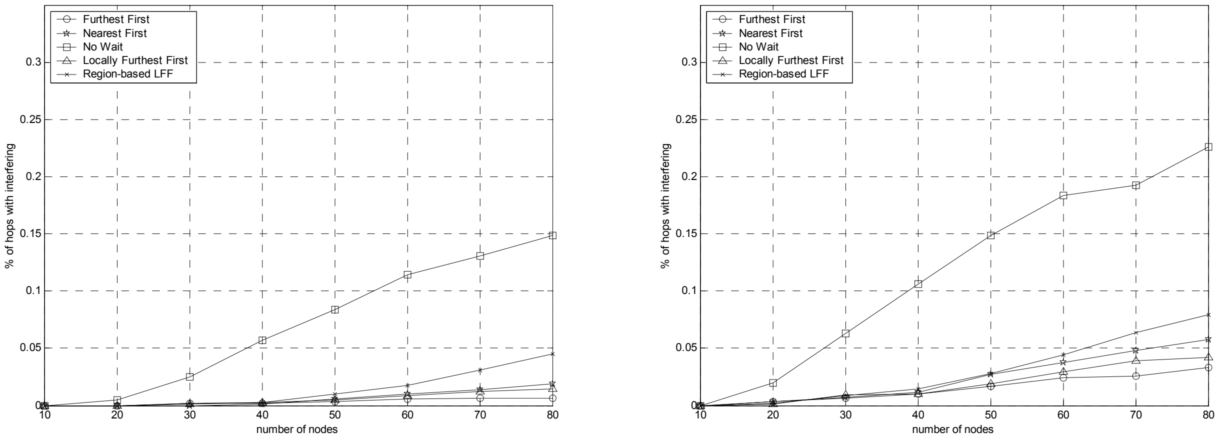
Number of frequency = 12

Number of frequency = 10



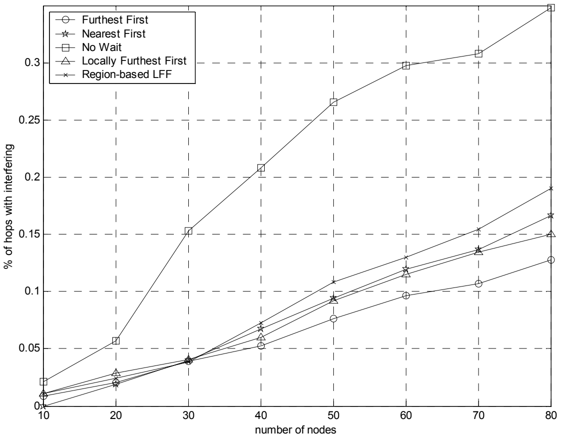
Number of frequency = 8

Figure 23. Absolute diversity percentage on the path



Number of frequency = 12

Number of frequency = 10



Number of frequency = 8

Figure 24. The percentage of hops with interfering links

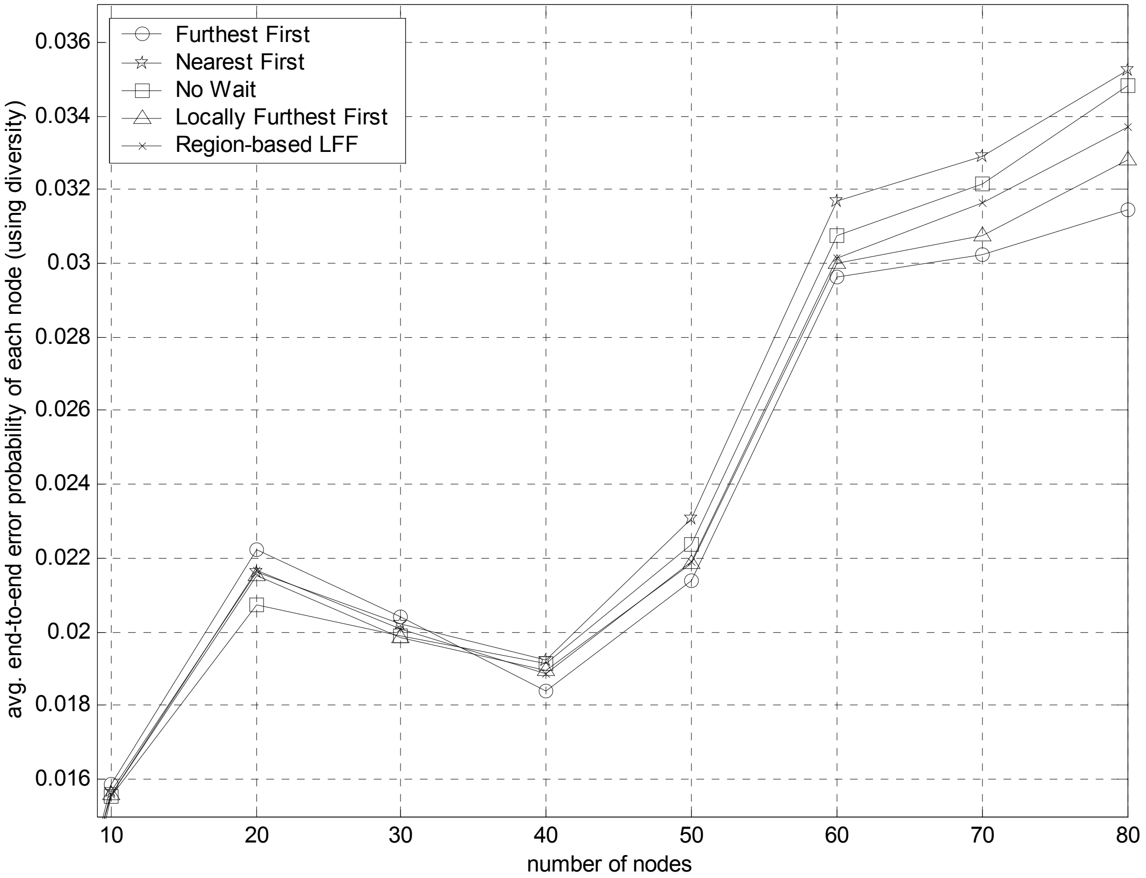
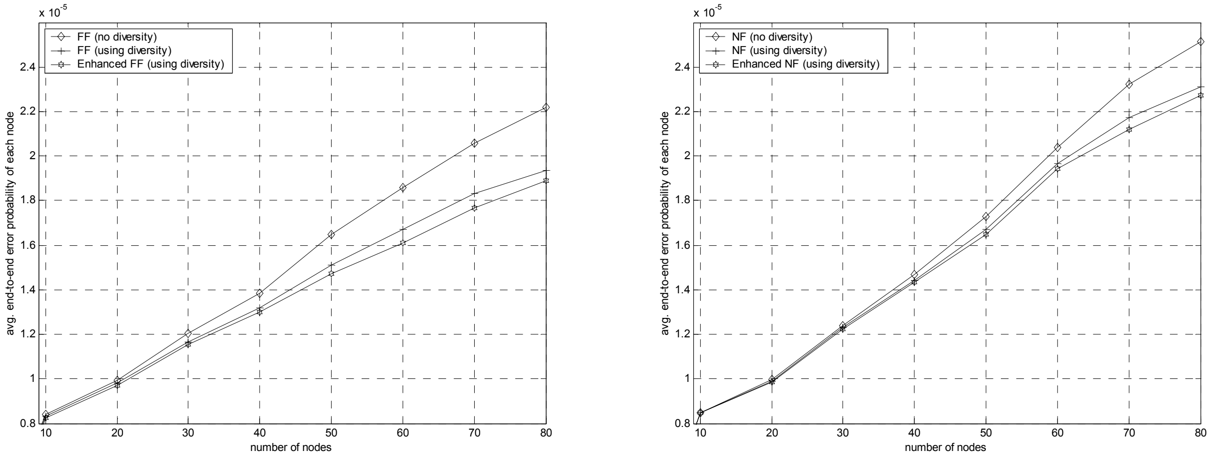
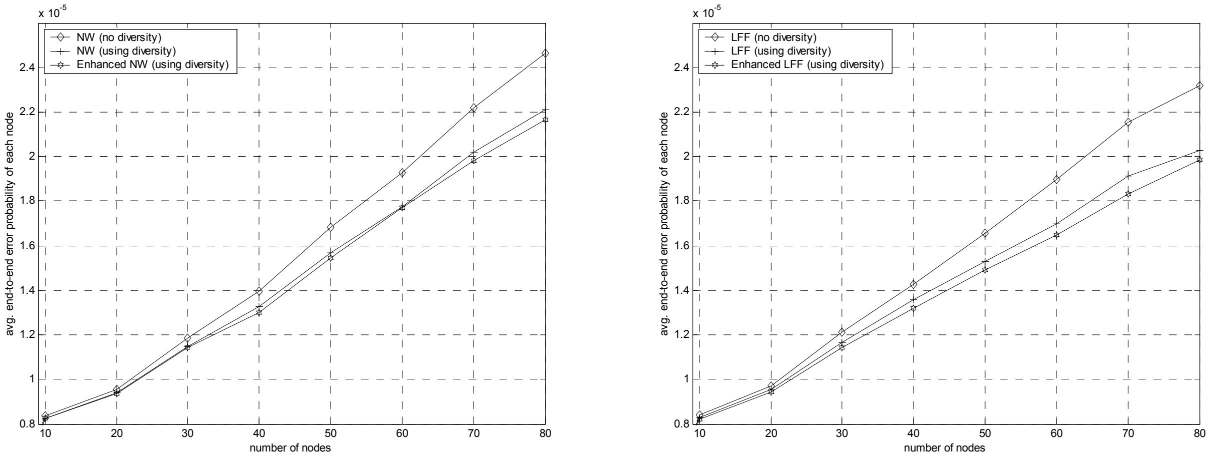


Figure 25. Avg. probability of error of each node with random SNR (with diversity)



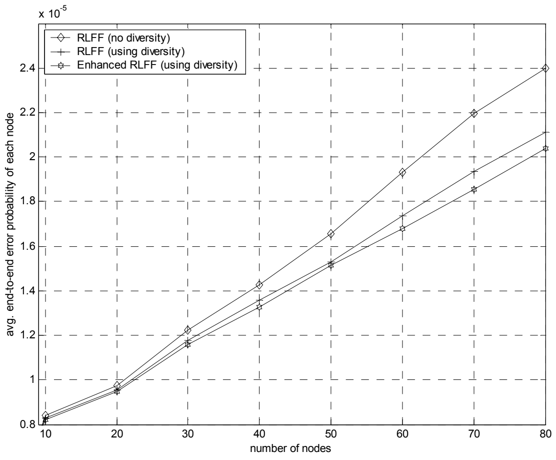
FF Scheme

NF Scheme



NW Scheme

LFF Scheme



R-LFF Scheme

Figure 26. Improvement in end-to-end error probability by adding diversity to the relay node