Dynamic Multi-Frequency, Multi-Hop Wireless Cellular Networks

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ABSTRACT - **Multi-hop relaying in cellular networks can greatly increase capacity and performance by exploiting the best available relay links to a base station. We envision an environment in which relay networks are dynamically formed when performance on the radio access network is degraded and then dissolved when the performance improves or the radio spectrum on which the relay network is operating is reclaimed. Each relay network operates on a different frequency band. Likewise, a relay network may channelize its frequency band to** offer **non-interfering links between the mobile nodes within a single relay network. In this paper, we propose a set of algorithms used to form such relay networks on-demand. Each algorithm provides a simple and distributed frequency assignment scheme. We evaluate these algorithms in terms of several metrics indicating the overhead of the relay network formation. The evaluation results show that having nodes outmost from the BS initiate route discovery first is the best approach for reducing the formation overhead. We also measure the throughput of the resulting relay networks. The results show that there is a large performance gain when using multiple frequencies in a relay network. Further, the performance of the network using multiple frequencies based on our simple frequency assignment is very close to that of a network using optimal frequency assignment.**

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TOPIC - **Mobile network architectures** - mobile networks beyond the 3rd generation

1. INTRODUCTION

Mobile nodes in traditional wireless cellular networks communicate through centralized base stations (BS) in a pre-defined spectrum. All nodes within a cell share common spectrum. To improve the performance of such cellular networks, several studies on multi-hop wireless cellular networks, also called hybrid wireless networks, have been undertaken [1][2][3]. Several papers [1][2] address relaying in GSM networks. We instead investigate a third generation (3G) wireless system, CDMA2000 1xEVDO, in which the sharing of communication resources is done via a combination of regulating power and time division multiplexing [4][5].

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. If the BS can schedule nodes with better signal quality more often, then a higher average bit rate for the network can be achieved.

In this paper, we envision a multi-hop wireless cellular network that uses 1xEVDO as the downlink to the BS. Multiple relay networks are *dynamically formed* when performance on the radio access network is degraded. A disjoint frequency band for each relay network is allocated by the BS dynamically. In this way, multiple non-interfering relay networks may operate in parallel.

The dynamic nature of these networks motivates the need for an explicit procedure for mobile nodes forming a relay network. Moreover, it requires that every mobile node be able to communicate over a wide range of frequency bands. We assume that each mobile node is equipped with an agile radio in addition to a cellular interface to meet this requirement. Nodes can dynamically change frequencies and communication formats to be most suitable based on availability, interference level, or prior arrangement [6]. The cellular interface is leveraged so that the BS may broadcast information during the network formation.

In addition to forming relay networks in disjoint frequency bands, we allow the band used by a single relay network to be divided into multiple orthogonal frequencies to construct a relay network comprised of non-interfering links. This allows multiple nodes within range of each other to transmit simultaneously without relying on a MAC protocol or distributed scheduling algorithm to resolve collision and contention.

In this paper, we present three relay network formation algorithms. Each algorithm first determines which nodes are best suited for acting as a bridge between the relay network and the BS, and designates these nodes as gateway (GW) nodes. In the next phase, the algorithms discover a path from each node through the relay network to the GW node. The difference in the three algorithms is the schedule by which nodes find their path to the GW node. Each algorithm also provides a simple and distributed frequency assignment scheme to build relay networks with non-interfering links to improve network throughput. We evaluate these algorithms in terms of the overhead of the relay network formation.

We also measure the throughput of the resulting relay networks in three scenarios: (1) relay networks using a single frequency; (2) relay networks using multiple frequencies assigned by our distributed algorithm; and (3) relay networks using multiple frequencies with optimal frequency assignment.

The results lead us to conclude that having nodes outmost from the BS initiate route discovery first is the best approach for reducing the relay network formation overhead. The results also show that using simple and distributed frequency assignment can achieve high throughput gains over using networks that uses only a single frequency. This simple frequency assignment algorithm achieves 80-85 % of the optimal average throughput.

The rest of the paper is organized as follows. In section 2, we present the network model for dynamic multi-frequency, multi-hop wireless cellular networks. In section 3, basic operations used for relay network formation and frequency assignment are explained. In Section 4, we present our simulation environment and results. In Section 5, we briefly discuss related work in the area. Section 6 concludes this paper.

2. NETWORK MODEL

In this paper, we focus on a single cell environment in which there is a BS and several mobile nodes.

Figure 1 shows an example in which several groups of nodes form relay networks to the BS. In this example, 7 mobile nodes communicate with the BS initially. The BS determines to make new frequency band available on which a relay network is formed; it advertises this frequency band, B_{r1}. Then, the nodes form a relay network r_1 operating on B_{r1}. At some time later, the BS may advertise a new frequency band B_{r2} on which a new relay network r_2 is formed.

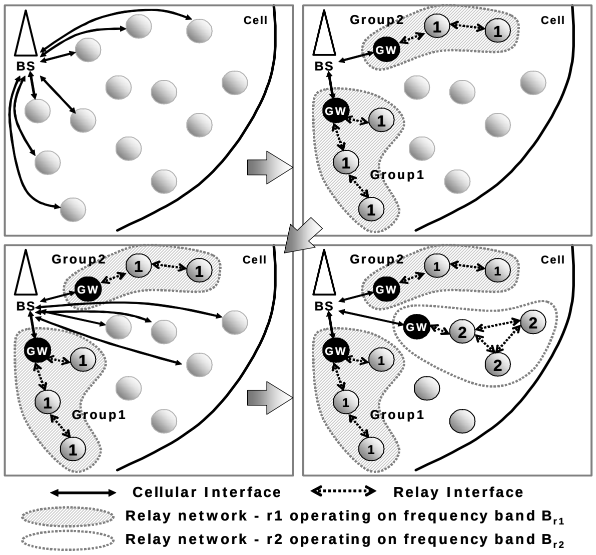


Fig. 1. Example of relay network formation

2.1. Frequency Band Allocation

A frequency band is allocated by the BS whenever a relay network is formed. Let $\boldsymbol{S}$ be the set of all available radio frequency bands, $\boldsymbol{S} = \{B_1, B_2, B_3, \ldots, B_N\}$, and $\boldsymbol{R}$ be the set of relay networks currently operating, $\boldsymbol{R} = \{r_1, r_2, \ldots, r_R\}$. If B_{ri} and B_{rj} are frequency bands on which relay network r_i and $r_j \in \boldsymbol{R}$ operate, respectively, they should satisfy the requirements: (1) $B_{ri} \in \boldsymbol{S}$ and $B_{rj} \in \boldsymbol{S}$, (2) $B_{ri} \neq B_{rj}$.

2.2. Frequency Assignment

Each frequency band may be divided into multiple orthogonal frequencies. For example, a band B_{ri} consists of the set of orthogonal frequencies, $\boldsymbol{F_{ri}} = \{f_1, f_2, \ldots, f_K\}$, where K is the maximum number of orthogonal frequencies in B_{ri}. These frequencies may be used to construct a relay network comprised of non-interfering links so that multiple nodes within range of each other may transmit simultaneously without relying on a MAC protocol or distributed scheduling algorithm to resolve collision and contention.

2.3. Dynamic Formation and Dissolution of the Relay Network

The formation and the dissolution of each relay network are performed through the following steps:

(1) If the BS schedules a large number of nodes that have poor signal quality, and hence low bandwidth, it may decide to make new frequency band available on which a relay network is formed.
(2) The BS chooses an available band and broadcasts the frequency band information over the cellular control channel so that all nodes in the cell receive it simultaneously. This information contains all available orthogonal frequencies in the band. The first frequency is used as a *control channel* to deliver signaling messages for the relay network formation.
(3) Some mobile nodes form a relay network operating on the introduced band.
(4) Once the relay network is created, the BS schedules only the GW nodes for transmission. Nodes in the relay network forward data between the GW and the destination node.
(5) At a later time, the relay network may be dissolved and nodes return to using the cellular interface with the BS.

In this paper, we present the relay network formation algorithms used for step (3).

3. FORMATION AND FREQUENCY ASSIGNMENT ALGORITHMS

Each relay network is formed in two phases. In Phase I, GW nodes are chosen for each group. The transmission radius of a node in the relay network is very small compared to the cellular coverage. For example, unlike the cellular interface which provides the typical radius of 10 ~ 20km, the maximum effective transmission range of IEEE 802.11 is 250 meters. Thus, a relay network generally consists of several isolated groups of mobile nodes. In Figure 1, the relay network r_1 consists of two isolated groups of mobile nodes. Each group needs at least one GW node to act as a bridge between the BS and the group.

Phase II consists of two steps. In the first step, the nodes join the relay network by establishing a path to one of the GWs. In the second step, while returning a route reply (*RREP*) message to the source node of a route request *(RREQ)* message, the GW and intermediate nodes on the reverse path are responsible for assigning an orthogonal frequency to links on the path. The frequency assignment algorithm describes a simple and distributed manner to make an assignment.

We use a modified version of AODV [7] as the ad-hoc routing protocol to find the path from the mobile nodes to the GW. Mobile nodes broadcast a *RREQ* to find a path to the GW. Intermediate nodes set up the reverse path to the source node and then forward the *RREQ* to the GW. In modified AODV, the *RREQ* contains path information like DSR [11]. Each intermediate node appends its identification to the *RREQ* before forwarding it. Thus, when receiving the *RREQ*, the GW node can learn members of specific groups within the relay network.

We leverage two optimization features of reactive ad-hoc routing protocols to reduce the overhead of forming relay networks. First, a node may *passively learn a route* to a destination if it is part of a longer path to the 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. Note that this precludes the BS from obtaining a full list of nodes on the relay network during the formation process. We discuss the impact of this in section 3.3.

These two features can greatly reduce the number of messages flooded to find routes. In order to make the utmost use of the passive route learning, intuitively the furthest node from the BS is the best choice to launch a route request first. This will greatly reduce the load at the GW node also because many nodes will passively learn routes. To fully leverage the immediate response to a *RREP*, scheduling the nodes nearest the BS to launch a *RREQ* first is the best choice.

Motivated by these observations, we propose the three relay network formation algorithms which use node's location information - two centralized algorithms: Furthest First (FF), Nearest First (NF); and a distributed algorithm: Locally Outmost First (LOF). The algorithms dictate the scheduling by which nodes send out their own *RREQ*.

3.1. Phase I – GW Discovery

In our environment, the BS broadcasts the frequency band information on which a relay network is formed over the cellular control channels so that all nodes within the cell receive it simultaneously. A pre-agreed upon channel within the relay network frequency band is define as the control channel used to establish and maintain the relay network.

To select GW nodes, every node forming a new relay network periodically broadcasts a neighbor advertisement (*NADV*) message over the control channel as soon as it receives new frequency band information. The *NADV* contains the identification of the sending node and a metric indicative of the received signal quality from the BS. The GW nodes chosen have the best received signal quality compared to the other neighboring nodes.

For many reasons, a node further away from the BS may have better signal quality than another node closer to the BS. However, it has been showed that there is a strong correlation between the distance of a base station and its signal strength [12][13]. Moreover, since noise and interference can cause the received signal strengths to fluctuate significantly over time, the received signal strength of each node can be represented as a function of distance from the BS in the cellular networks [14]. Motivated by these observations, we use the distance from the BS as the metric indicative of received signal quality in this paper.

Whenever a node receives a *NADV* message from its neighbors, it compares its distance from the BS with its neighbor's. If the node has the shortest distance compared to all neighbors, the node acts as a GW node as follows:

```
GW_Discovery()

    $D_i$ = Distance from the BS of node i;
    Receiving NADV from all neighbors;
    $D_k$ = the distance of neighbor k;
    If ( $D_i$ == min ($D_i$, $D_k$)) for all neighbors k,
    then node i acts as a GW node;
```

If several neighbors have the same shortest distance, one is selected randomly.

3.2. Phase II – Joining the Relay Network

In this section we discuss the procedure by which nodes join a relay network. This consists of two steps: initiating route discovery, and assigning frequencies on each link in the relay network if the frequency band for a relay network is segmented into multiple frequencies.

3.2.1. Step 1: Initiating a Route Discovery

The difference between our formation algorithms is the schedule by which nodes initiate path discovery.

Baseline. As a baseline, we consider the case in which every node joining the relay network initiates a route discovery just after GW discovery phase. In this case there is no schedule for initiating path discovery. This is very simple and easy to implement, but runs the risk of severe congestion on the relay network during the formation phase because every node sends out *RREQ* almost simultaneously. It may also cause overloading the GW node with many *RREQ*s during a short time period.

Furthest First(FF). To solve the problem of GW overload and congestion during network formation we exploit the ability of nodes to passively learn routes. If a node can passively learn a route, it will not generate a *RREQ*. This optimization reduces both the congestion caused by the potential *RREQ* storm in the relay network, and the load on the GW. From this observation, the most extreme schedule is to have the nodes furthest from the BS launch *RREQ*s first, so that as many nodes will passively learn a route to the BS as possible.

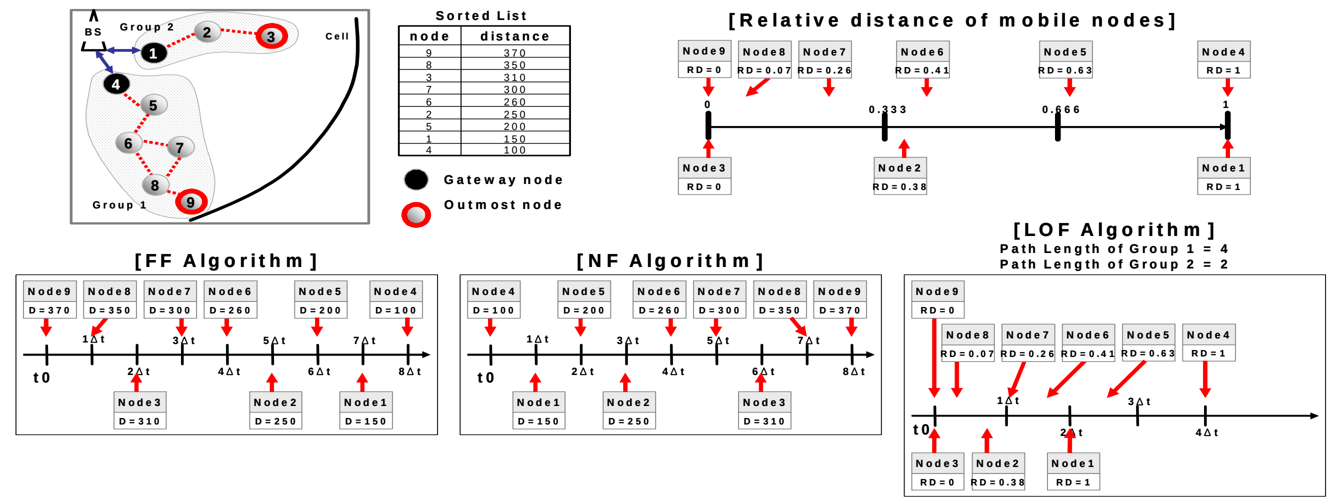
Note that the formation algorithm schedules the *initiation* of each node's route discovery. It is impossible to anticipate which node will be located at the end of the longest path from the GW nodes until all nodes complete the route discovery. However, the nodes furthest from the BS generally have the greatest possibility to have the longest path from the GW nodes. This algorithm thus forces the furthest node to launch *RREQ* first.

It is impractical for a node to learn the exact location of all other nodes, but we evaluate this algorithm to understand the performance of a strictly scheduled formation protocol. We therefore assume that the BS may act as a central controller and track each node's location in the cell. The BS forces the node furthest from the BS to launch a *RREQ* first.

If a node is not on the path between the furthest node and the BS, it will not passively learn a route. To ensure these nodes learn a route, the BS schedules each node to launch its own *RREQ* in decreasing order of distance from the BS at every certain time interval, Δt.

As shown in Figure 2, based on the location information of the nodes, node 9 (furthest from the BS) is scheduled to send out its *RREQ* at time $t0$; node 8 (the next furthest node) is scheduled at $t0+\Delta t$, and so on. After node 9 launches its *RREQ* at time $t0$, nodes 5, 6, and 8 may passively learn a route to the BS. Thus, if they receive the *RREP* before $t0+6\Delta t$, $t0+4\Delta t$, and $t0+\Delta t$, respectively, they will not send out their own *RREQ*s.

```
Relay_Network_Formation( ) {
   Receiving the broadcast from the BS;
   GW_Discovery();
   /* for LOF */
   Outmost Node_Discovery();

   t0 = finishing time of GW discovery;
   D_i = node i's distance from the BS;
   Node i is scheduled to initiate
      the route discovery at time T_i
      in centralized or distributed manner;

   switch(formation_algorithm) {

case Furthest_First (FF) :
   SD_i = the index of the node i
            in the sorted node list
            in decreasing order of
            distance

   T_i = t0 + (SD_i * Δt);

case Nearest_First (NF) :
   SI_i = the index of the node i
            in the sorted node list
            in increasing order of
            distance

   T_i = t0 + (SI_i * Δt);

case Locally_Outmost_First (LOF) :
   If (node i is outmost node)
   then
      T_i = t0;  /* immediate starting */
   else {
      ReceivingGroupInformationfromtheBS( );
      Calculating the relative distance RD_i;

      T_i = t0 + (RD_i * PL * Δt );
   }
```



Sorted List

node	distance
9	370
8	350
3	310
7	300
6	260
2	250
5	200
1	150
4	100

Fig. 2. Formation algorithms and example of scheduled time

There are two major drawbacks with this algorithm. First, the BS must know the exact location of all nodes, which is not practical. Second, since it is impossible to anticipate which nodes may passively learn a route to the BS in advance, the controller must use a fixed schedule. Thus, if a node passively learns a route before its scheduled time, as with nodes 5, 6, and 8 in Figure 2, the time slots assigned to the nodes are wasted. This introduces unnecessary latency into the network formation process.

Nearest First(NF). When a node already having a forward path to the GW receives a *RREQ*, it can immediately return a *RREP* to the source node. In so doing, the majority of the *RREQ* traffic is replied to without being forwarded to the GWs. Therefore, having the node nearest to the BS initiate a *RREQ* first will also lower load on the network. As with FF, this scheme requires the BS to act as a central controller.

For example, in Figure 2, if node 6 has a route to the BS before receiving the *RREQ* generated by node 9 at time $t0+8\Delta t$, it returns a *RREP* to node 9 immediately.

In addition to requiring a centralized controller, this algorithm has the additional drawback that almost all nodes must launch a *RREQ*, at least to reach the node preceding them to the GW.

Locally Outmost First (LOF). FF and NF reduce the number of signaling messages flooded in the network. However, mobile nodes may experience long latency due to the strict, sequential scheduling. They are, moreover, not practical because the centralized scheduler must know the distance to all nodes. We present a distributed algorithm, called *Locally Outmost First* (LOF), to receive the benefits of FF and NF, and the potential low latency of the baseline case. Without any centralized controller, this algorithm allows each node to make a schedule for its own route discovery based on its distance and the group information broadcast by the BS.

This algorithm is composed of two steps - outmost node discovery and scheduling. A relay network consists of several isolated groups of mobile nodes as shown in Figure 1; each group can form the relay network independently. In this algorithm, all outmost nodes in *each group* initiate a route discovery first just after outmost node discovery. Thus, several paths will be discovered simultaneously. The *outmost node* has the greatest distance from the BS compared to all neighbors within its transmission range. Each group has at least one outmost node. For example, nodes 9 and 3 act as the outmost node in groups 1 and 2, respectively, in Figure 2.

(1) Outmost Node Discovery

This procedure can be overlapped with GW discovery.

During the GW discovery, each node compares its distance from the BS with the neighbor's. If a node has the greatest distance compared to all neighbors, this node becomes an outmost node as follows:

```
Outmost Node_Discovery( )

    $D_i$ = Distance from the BS of node i ;
    $D_k$ = the distance of neighbor k;
    If ( $D_i == \max(D_i, D_k)$ ) for all neighbors k,
    then node i acts as a outmost node;
```

If several neighbors have the same greatest distance, one is selected randomly.

(2) Scheduling

The GW node initially delivers the group information to the BS when it receives *RREQs* sent from the outmost nodes, which is passed through a new path. Then, the BS broadcasts the group information so that mobile nodes in the cell exploit it. The group information contains the ID of the GW, the distance of the GW (D_G), the ID of the outmost node that sent the *RREQ*, the distance of the outmost node (D_O), and the hop count of the path (*PL*).

With the characteristic of flooding, all nodes in the group receive at least one *RREQ* sent from the outmost nodes. If a node receives a *RREQ* from an outmost node and the BS broadcasts group information including the outmost node and a GW, the node belongs to the same group as the outmost node and the GW. Moreover, the node may be on one of the paths between the outmost node and the GW. Thus, based on the broadcast group information and the information in received *RREQ*, each node can calculate its *relative distance* between the GW node and the outmost node and then makes a schedule for its own route discovery with the relative distance as follows:

Relative distance of node *i*

$$RD_i = 1 - \frac{D_i - D_G}{D_O - D_G} \qquad \textbf{Eq. (1)}$$

D_i = the distance from the BS of node *i*;
D_G = the distance from the BS of GW node;
D_O = the distance from the BS of outmost node;

PL = the hop count between the outmost node and the GW
T_i = the scheduled time of node *i*'s route discovery
$= t0 + (RD_i \times PL \times \Delta t)$

The relative distance has a value of the range [0..1]. A smaller value indicates that the node is closer to the outmost node.

As shown in Figure 2, since nodes 3 and 9 are outmost nodes, they send out *RREQ* simultaneously at time *t0*. Then, the intermediate nodes can calculate their relative distances based on the group information. For example, node 6 belongs to the group 1 in which the GW node and the outmost node are node 4 and 9, respectively. Node 4's distance is 100 and node 9's distance is 370. Thus, the relative distance of node 6 is 0.41. The hop count of the path is 4. Thus, node 6 makes a schedule for its route discovery at time $t0+1.64\Delta t$. *If it does not passively learn a route before* $t0+1.64\Delta t$, it sends out its own *RREQ* at the scheduled time. Since this scheduled time is inversely proportional to its relative distance, this algorithm makes use of the passive route learning.

3.2.2. Step 2: Assigning Frequency

Each node establishes a single path to a GW node. The GW nodes return a *RREP* to the source node on behalf of the BS. While returning the *RREP*, the GW and intermediate nodes on the reverse path are responsible for assigning a non-interfering frequency to links on the path. In this section, we present a simple and distributed frequency assignment scheme.

We define the used frequency information of a node, *UFI*, as the set frequencies used on all of its incident links. To make a local frequency assignment when a path is being established, a node requires the *UFI* of all nodes within its transmission range. This information is received in two ways: first, the *NADV* messages periodically broadcast include the *UFI* of a node. Second, the *UFI* is included in the *RREP* generated by a node. The algorithm for selecting a frequency on a link follows.

```
Frequency_assignment( )

$Af_i$        = set of available frequencies of node i ;
$UFI_i$       = set of frequencies used by node i ;
$UFI_j$       = set of frequencies used by neighboring node j ;
$UFI_{(i-1)}$ = set of frequencies used by the previous node on the reverse path ;
$f_{i-1}$     = frequency for upstream link of node i assigned by the previous node ;

/* Initial Condition */
  $Af_i = F_{ri}$;

/* When receiving NADV from a neighboring node j */
  /* recalculate Afi */
  $Af_i = Af_i \cap \overline{UFI_j}$ ;  return;

/* When receiving RREP from the previous node on the reverse path */
  /* recalculate $Af_i$ and $UFI_i$ */
  $Af_i = Af_i \cap \overline{UFI_{(i-1)}}$ ;
  $UFI_i = UFI_i \cup \{ f_{i-1} \}$;

  /* assign a frequency */
  If ( $Af_i$ != Ø )
     /* There is an available frequency */
     then { choosing a frequency $f_i$ from $Af_i$ and assigning it to its next-hop-link ;
              $Af_i = Af_i \cap \overline{\{ f_i \}}$;
              $UFI_i = UFI_i \cup \{ f_i \}$;
            }

     /* There is no available frequency */
     else { picking up a frequency $f_i$ from $UFI_{(i-1)}$ except $f_{i-1}$ and
              assigning it to its next-hop-link ;
              $UFI_i = UFI_i \cup \{ f_i \}$;
          }

Inserting $UFI_i$ and $f_i$ into RREP message and returning to the next node ;
```

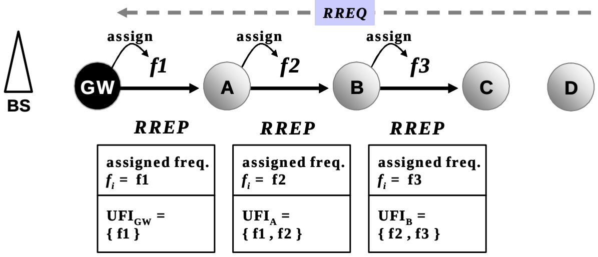


Fig. 3. Frequency assignment

Each node *i* in the relay network *ri* maintains a set of available frequencies in the relay network, Af_i. Initially $Af_i = F_{ri}$, all frequencies in the relay network. When a node receives UFI_j from the *NADV* generated by node *j*, node *i* recalculates $Af_i = Af_i \cap \overline{UFI}_j$. When node *i* receives a *RREP* from node *i-1*, it is further recalculates $Af_i = Af_i \cap \overline{UFI}_{(i-1)}$. The node assigns a frequency to its next-hop-link by choosing from the resultant Af_i as shown in Figure 3.

If the node receiving the *RREP* has no available non-interfering frequencies, it may select a frequency that is already chosen by the previous nodes. In this case, the MAC protocol will resolve contention between the competing links, thus lowering network performance. In order to alleviate the degradation of network performance, the node picks up a frequency from $UFI_{(i-1)}$ except f_{i-1}.

3.3. Transient Behavior

In order to transfer the downlink data to the destination node, the BS needs to keep a list of nodes on the relay network. Thus, the GW node delivers the group membership information to the BS when it receives a *RREQ* passed through a new path. Because some intermediate nodes which have a route to the BS may immediately return a *RREP* to the source node, some *RREQ*s do not reach the GW node. Thus, group information sent by the GW may be incomplete even if the source node already joined the relay network. In this case, the BS will continue to use its cellular interface to communicate with the source node in the downlink until it receives data from the node via the relay network on the uplink. At this time the BS will have a record of the node being in the relay network group served by a GW and transfer the next downlink data through the relay network.

Due to mobility, links in the relay networks may break, and new nodes may join a relay network. In these cases the effected nodes issue an *RREQ* as if it was joining a relay network for the first time. Any node receiving the *RREQ* responds with an immediate *RREP* as during relay network formation. Because the nodes store the used frequency information, frequency assignment on the new link is made as during network formation.

4. PERFORMANCE EVALUATION

We simulated the formation algorithms in NS-2 v.2.1b9a to compare them in terms of the overhead during network formation. OPNET was used to measure the throughput gains achieved by the single- and multi-frequency relay networks. The throughput of the multi-frequency relay networks resulting from LOF were compared with those with optimal frequency assignments.

4.1. Simulation Environment

The air interface to all nodes when no relay network is in operation is based on a 1xEVDO. This interface is also used between the GW nodes and the BS when a relay network is in operation. We use a simplified approximation of a 1xEVDO system in which the BS schedules the mobile nodes on the forward cellular link with 3 classes of data rate: 2.5 Mbps, 921 Kbps, and 153 Kbps, according to the received signal quality of the nodes.

The relay network uses 802.11a. The multi-frequency relay network we consider can use up to 12 orthogonal frequencies. 802.11a resolves contention of a channel by using an RTS-CTS exchange between nodes before they can transmit. To avoid contention, nodes within two hops should use different frequencies.

The experiments are based on a 886x886m^2 6-sector cell with up to 100 mobile nodes. In this scenario, each node in the relay network downloads 4 Mbits data from an FTP server. Table 1 summarizes the simulation parameters.

Parameter	Value
Cell size (BS at center)	886m X 886m
N (# of nodes / cell)	1 ➔ 100
# of sectors / cell	6 sectors
DRC_i (Classes of HDR links)	DRC_1 : 2457 Kbps DRC_2 : 921 Kbps DRC_3 : 153 Kbps
Downloaded file size	4 Mbits / user
Application	FTP/TCP
Advertised frequency band	Frequency band used for 802.11a
# of orthogonal frequencies	12
Air interface range	115m

Table 1. Simulation parameters

The value of Δt used in the formation algorithms discussed in Section 3 is initially broadcast by the BS and can affect the performance of the formation algorithms. If Δt is extremely small, all nodes initiate a route discovery almost simultaneously. Thus, all algorithms run like the baseline case and cannot exploit the optimization features. If it is extremely large, each algorithm can fully exploit the optimization features but formation latency may be large. In a CDMA2000 1xEvDO system, each mobile node can occupy maximum 16 timeslots (each of which is 1.67 msec) at its turn. Thus, in order to synchronize with this system, Δt is set to 26.72 msec in this simulation.

4.2. Comparison of the Formation Algorithms

We use three metrics to compare the performance of our formation algorithms: *signaling traffic*, *formation latency*, and *GW load* as shown in Table 2.

They indicate the *overhead* of the relay network formation. Since relay networks are typically formed during congested periods, or when the network is experiencing poor performance, formation latency is critical. Signaling traffic generated indicates the degree of network congestion during the network formation. The processing load at the GW nodes is proportional to the traffic intensity of the cellular interface between the BS and the GW nodes during the formation process.

For the comparison, 100 different network topologies are generated in each case of 10 to 100 nodes. Each data point is the average over the runs.

The results of the simulation are shown in Figures 4-7. It is clear that all algorithms incur trade-offs. In general, the algorithms with the strict scheduling like NF and FF have the highest latency (Fig. 5) due to their sequential nature, while those with more parallelism have lower latency at the expense of higher signaling traffic (Fig. 4) and GW load (Fig. 6).

NF has the highest latency, but the fewest messages to hit the GW nodes. Even though BL has low latency, the signaling traffic and the load at GW node during network formation is about three times of that when using FF and NF. LOF has good performance in terms of signaling traffic and load at the GW node, but high latency at high node density.

Therefore, we define the *weighted overall overhead* of each algorithm as shown in Table 2. It is the summation of relative value of the three metrics which are given different weights according to their importance.

Performance of the formation algorithms **(S = type of formation algorithm (e.g. BL, FF, NF, LOF))**		
Name	Description	Formula
Signaling Traffic	Total number of routing messages received by all mobile nodes forming the relay network	**M(S) =** $\sum_{i=1}^{N} msg_i$ **, where** msg_i **= # of received messages by node i**
Formation Latency	The time elapsed between the first *RREQ* and all nodes having a route to the BS	**L(S) =** $t\_final - t\_init$ **, where** t_final **= time when all nodes have a route to the BS** t_init **= time when the first RREQ sends out**
GW Load	Total number of routing messages received by all GW nodes	**G(S) =** $\sum_{g=1}^{G} g\_msg_g$ **, where** g_msg_g **= # of received messages by GW node g**
Weighted Overall Overload	Summation of relative overhead compared to the other algorithms each of which has different weight according to the importance of the metric	**RM(S)=relative signaling traffic of algorithm S=** $\frac{M(S)}{\max(M(BL), M(FF), M(NF), M(LOF))}$ **RL(S)=relative formation latency of algorithm S =** $\frac{L(S)}{\max(L(BL), L(FF), L(NF), L(LOF))}$ **RG(S)=relative GW load of algorithm S =** $\frac{G(S)}{\max(G(BL), G(FF), G(NF), G(LOF))}$ **WO(S)=weighted overall overhead of alg. S =** $(\alpha \times RM(s)) + (\beta \times RL(s)) + (\gamma \times RG(s))$ $\alpha + \beta + \gamma = 1$

Throughput of the resulting relay network		
Name	Description	Formula
Overall Network Throughput	The cumulated throughput of the relay network until all nodes complete their FTP transaction	Rt_i **= FTP response time of node** i FS **= Download file size of each node** **Longest Response time = max (** Rt_i **), 1 <=** i **<= N** **Overall network throughput** $= \frac{FS \times N}{\max(Rt_i)}$
Average Node Throughput	Average throughput of each nodes in the relay network	**Average node throughput =** $\frac{FS}{\left(\frac{\sum_{i=1}^{N} Rt_i}{N}\right)}$

Table 2. Performance metrics

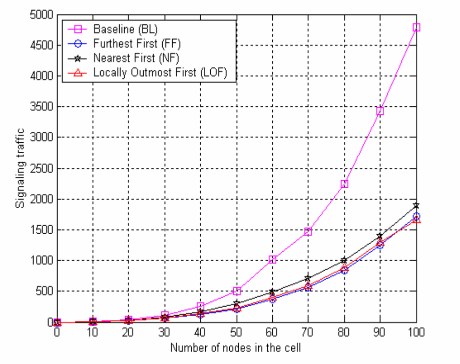


Fig. 4. Signaling traffic

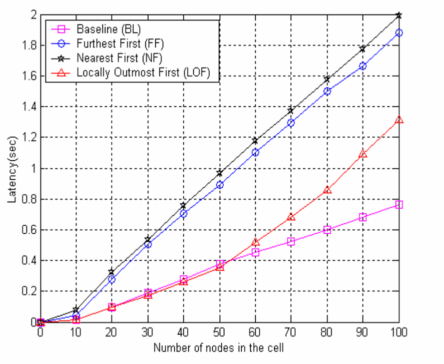


Fig. 5. Formation latency

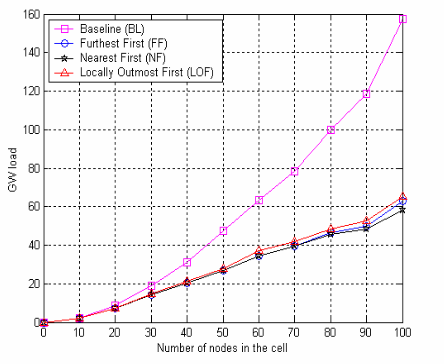


Fig. 6. Load at GW nodes

In Figure 7, β and γ are set to be equal, meaning that low latency and low load on the GW are of equal importance. We evaluate the overhead over the range of when the signaling traffic is considered highly unimportant ($\alpha = 0.01$), through the case in which all three metrics are of equal importance ($\alpha = \beta = \gamma = 0.33$). As shown, LOF is the best overall performing algorithm in terms of formation overhead.

4.3. Throughput

Since LOF is the best overall performing algorithm, we measure the throughput of the relay networks resulting from LOF using OPNET. We consider both single- and multi-frequency relay networks formed by LOF. We also consider a multi-frequency relay network with optimal frequency assignments as discussed below.

We use two metrics to compare the throughput of the relay networks: *overall network throughput* and *average node throughput* as shown in Table 2.

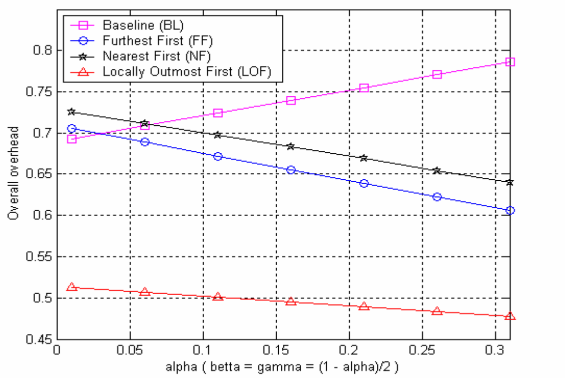


Fig. 7. Overall overhead ($\beta = \gamma = (1-\alpha)/2$)

The overall network throughput indicates the total throughput of the relay network as measured at the BS until all nodes complete their FTP transaction. Thus, it generally depends on the throughput of the node with the lowest data rate. The average node throughput is calculated based on the average FTP response time of the nodes in the relay network.

4.3.1. Simulation scenario

We measure the throughput of the resulting relay networks in three scenarios as follows:

- **Scenario 1**: A relay network uses a single frequency on all links.

- **Scenario 2**: Each relay network may use up to all 12 available frequencies. All nodes in the relay network make frequency assignments according to the proposed frequency assignment scheme in section 3.2.2.

  In this scenario each node assigns a frequency to the next-hop-link based on the Af_i calculated as described in Section 3.2.2. This method cannot be guaranteed to make optimal non-interfering frequency assignments for the following reasons. First, when choosing a frequency, each node cannot consider the subsequent frequency assignment of other nodes on a different branch of the relay network. As shown in Figure 8, while establishing a path, the used frequency information shared with nodes D and B will not include frequency *f3*. Thus, they may each assign *f3* to the link to node E and C, respectively, which will result in contention on these links. In this case the 802.11a MAC protocol will arbitrate the transmission of the nodes and they will achieve lower throughput.

  Second, the proposed frequency assignment scheme ignores the fact that a node's interference range may be greater than its transmission range. As shown in Figure 8, node A and node X are not within transmission range and belong to different group. As a result, the two nodes may assign the same frequency, *f2,* to the next-hop-link.

  Because these nodes are not within transmission range, the RTS-CTS exchange will not occur between these nodes. Instead, the nodes will interfere with each other resulting in higher bit error rates and lower throughput.

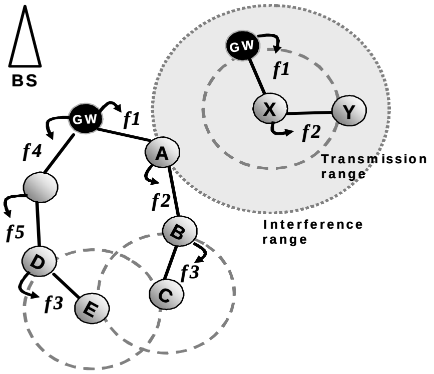


Fig. 8. Potential Interference

- **Scenario 3**: As with scenario 2, each relay network may use up to 12 frequencies. Unlike scenario 2, the frequencies are assigned by a centralized assignment scheme based on the interference constraint in [8]. In order to maximize network throughput, this algorithm assigns a channel to the link based on an interference constraint that considers a node's interference range as well as transmission range. This scheme makes optimal frequency assignments resulting in no contention and minimum interference.

4.3.2. Single Frequency Relay Networks

In this section, we examine the performance gain of the single-frequency relay network (scenario 1) over the pure 1xEVDO system.

In a CDMA2000 1xEVDO system, mobile nodes measure their received Signal to Noise plus Interference Ratio (SNIR). Based on the received SNIR mobile nodes transmit a 4-bit data rate control (DRC) sequence to the BS to request a specific data rate [4][5]. Our simplified system supports data rates on the forward link of 153, 921, and 2.5 Mbps.

Considering a time period in which the DRC of all nodes is constant, if all nodes in the 1xEVDO network are backlogged, the typical 1xEVDO BS scheduling algorithms perform in a round robin fashion: each node is scheduled for the same amount of time at the rate supported by their DRC. The network throughput under these conditions is simply the weighted average of the throughput of all nodes in the 1xEVDO network.

Thus when there are active M nodes in the sector, the maximum achievable data rate of node i, R_hdr_i, and the maximum average data rate of the nodes, $\overline{R\_hdr}$, are given by

$$R\_hdr_i = DRC_i \times \frac{1}{M} \quad \text{, where } DRC_i = \text{data rate of node } i \qquad \textbf{Eq. (2)}$$

$$\overline{R\_hdr} = \frac{\sum_{i=1}^{M} R\_hdr(i)}{M} \qquad \textbf{Eq. (3)}$$

When using a relay network, the BS schedules the GW nodes instead of the members of the relay network. In this way, all nodes on the relay network share the data rate sustained on the link between the GW and the BS. We assume the BS schedules GW nodes proportionately with the number of nodes on the relay network that they support. For example, a GW node terminating a relay network with 4 nodes will be scheduled twice as often as a GW node terminating a relay network with 2 nodes. A single node is treated as a GW supporting a relay network of 1 node.

Thus a node can never achieve higher throughput acting as a single node than when a member of a relay network. In fact, if a node joins a relay network in which the GW node has a higher DRC than itself, its throughput will be increased. Thus, the maximum achievable data rate of node i, R_relay_i, occurs when a node is a member of a relay network. Likewise, the maximum average relay network throughput, $\overline{R\_relay}$ is achieved when all nodes join a relay network. These values are given by:

$$R\_relay_i = DRC_{gw} \times \frac{1}{M}, \text{ where } DRC_{gw} = \text{data rate of GW} \qquad \textbf{Eq. (4)}$$

$$\overline{R\_relay} = \frac{\sum_{i=1}^{M} R\_relay_i}{M} \qquad \textbf{Eq. (5)}$$

We compare the simulated throughput achieved with a single-frequency relay network with the theoretical maximum achievable throughput of a 1xEVDO system in which no relay network is used. The throughput for the relay networks were obtained using OPNET according to the parameters in Table 1. Figure 9 shows the example of results obtained from three random topologies of a cell with 30 nodes. It can be clearly seen from Figure 9 that a 1xEVDO system operating with relay networks has better node throughput than a pure 1xEVDO system. We stress that these results are extremely conservative; the 1xEVDO results are the maximum throughput which does not include protocol overhead, channel errors, etc., while the relay network throughput includes all such overhead. We thus expect the gains from the relay network to be significantly greater.

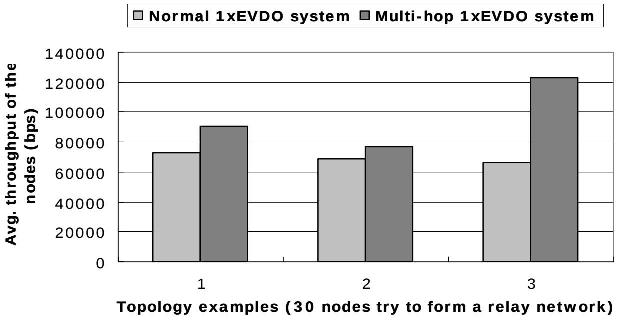
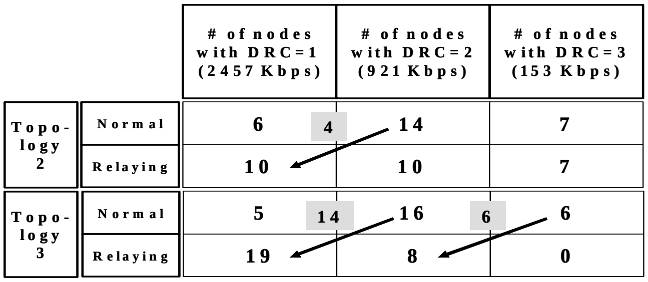


Fig. 9. Examples of throughput gain

We also note that the performance gain achieved by the relay network varies considerably from topology to topology. For example, the performance gain of the relay network over the pure 1xEVDO system is lower in topology 2 than with topology 3. This can be explained as follows.

A relay network improves the performance of a cellular network by exploiting the fact that GW nodes have throughput equal to or higher than the nodes they serve. From Table 3 it can be seen that, in topology 2, there are 7 nodes with DRC = 3 (supporting a data rate of 153.6 Kbps). When the relay network is formed in topology 2, all the nodes that have DRC = 3 originally keep the same data rate because the GW connecting the BS with these nodes also has DRC = 3. Thus these nodes achieve no performance improvement. The slight overall improvement in performance is because the 4 nodes that have DRC = 2 connect to a GW node with DRC = 1, thus increasing their throughput. In the case of topology 3, all the nodes that have DRC = 3 are connected through GW nodes that have DRC = 2. Thus a considerable improvement in performance is achieved in this topology.



		# of nodes with DRC=1 (2457 Kbps)	# of nodes with DRC=2 (921 Kbps)	# of nodes with DRC=3 (153 Kbps)
Topo-logy 2	Normal	6	14	7
	Relaying	10	10	7
Topo-logy 3	Normal	5	16	6
	Relaying	19	8	0

Table 3. Examples of nodes' data rate

4.3.3. Multiple Frequency Relay Networks

In this section we quantify the performance gains achieved by using a multi-frequency relay network. We consider both multi-frequency relay networks formed using the LOF algorithm and the frequency assignment procedure described in Section 3.2.2 (scenario 2), and those formed with an optimal frequency assignment (scenario 3).

Figures 10 and 11 show that if we exploit multiple frequencies, we can achieve higher overall network throughput and average node throughput. They also show that the simple frequency assignment scheme of Section 3.2.2 achieves almost the same overall network throughput and 80 - 85 % of the average throughput as when optimal channel assignment is used.

We note that as the number of nodes increases in the network, the improvement in performance of the optimal frequency assignment increases (Fig. 11). This is because it is more likely that the distributed frequency assignment algorithm will result in two nodes in different relay networks that are within interference range being assigned the same link frequency (see discussion of Figure 8).

Figure 12 illustrates this effect. This figure shows the nodes' received SNIR in each scenario with the same topology. It can be clearly seen that there is considerable improvement in SNIR when multiple frequencies are used, and that in some cases, the SNIR when using optimal frequency assignment is higher than when using distributed frequency assignment.

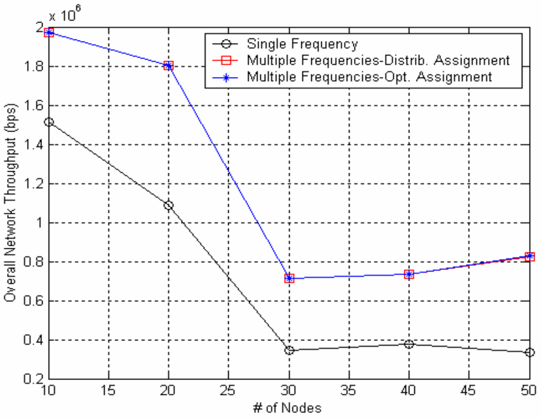


Fig. 10. Overall network throughput

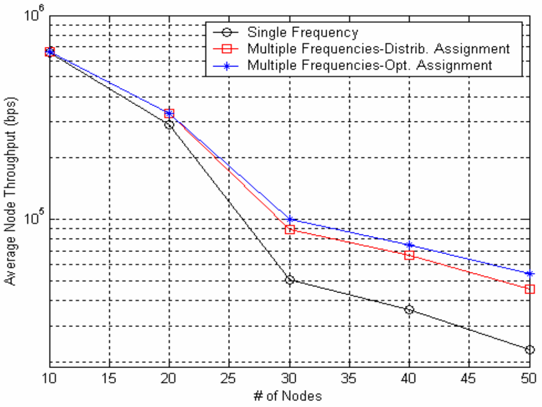


Fig. 11. Average throughput of the node

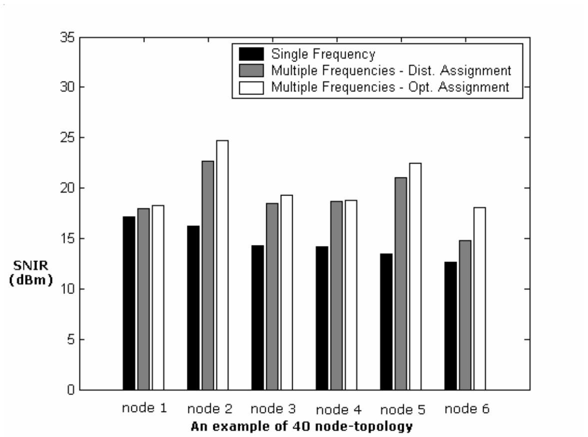


Fig. 12. Example of node's SNIR

5. RELATED WORK

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.

There has been a great deal of work on single frequency multi-hop wireless networks to improve cellular network performance [1][2][3]. Our work is most similar to the UCAN [3] system. However, this system is different from ours in that the relay network operates on a *single* frequency and 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 [8] [9][10]. In [10] it is shown that the network throughput can be significantly improved when mobile nodes are equipped with multiple interfaces and enabled to utilize multiple channels.

In order to form multiple orthogonal links efficiently, several channel assignment schemes are proposed in [8][9]. These efforts differ from ours in two key ways. First, they consider a *centralized* channel assignment scheme. 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 BS's broadcasts to disseminate information.

6. CONCLUSIONS

In this paper we analyzed the formation of relay networks for dynamic multi-frequency, multi-hop wireless cellular networks. We propose two centralized algorithms and one distributed algorithm for network formation, including determining which nodes are best suited for bridging the relay network and the BS, and the order of nodes to initiate a route discovery for establishing paths from nodes to the GW nodes. While establishing paths to the GW nodes, mobile nodes can make non-interfering frequency assignments to the relay links based on limited hop information. As a result, the number of interfering links can be reduced and hence we can achieve improved network throughput.

Our results show that schemes scheduling nodes furthest from the BS to initiate route discovery first make good use of passive route discovery and hence reduce the formation overhead. Moreover, they can build efficient relay networks which support high TCP throughput. The distributed LOF algorithm achieves a good trade-off between relay network formation overhead and latency.

We measured the throughput of the relay network resulting from the LOF algorithm. The results show that by exploiting multiple frequencies, we can achieve higher overall network throughput and average node throughput. Our simple and distributed frequency assignment scheme achieves 80 - 85 % of the optimal average node throughput.

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