Wireless Hierarchical Routing Protocol with Group Mobility (WHIRL)

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Abstract

In this paper we address the problem of routing in a large wireless, mobile network such as found in the automated battle field or in extensive disaster recovery operations. Conventional routing does not scale well to network size. Likewise, conventional hierarchical routing cannot handle mobility efficiently. In this paper, we propose a novel soft state Wireless HIerarchical Routing protocoL (WHIRL). We distinguish between the ”physical” routing hierarchy (dictated by geographical relationships between nodes) and ”logical” hierarchy of subnets in which the members move as a group (e.g., company, brigade, battalion in the battlefield). WHIRL keeps track of logical subnet movements using Home Agent concepts akin to Mobile IP. A group mobility model is introduced and the performance of the WHIRL is evaluated through a detailed wireless simulation model.

1 Introduction

Wireless, multihop, ad hoc networks are expected to play an increasingly important role in future civilian and military environments where wireless access to a wired backbone is either ineffective or impossible. The applications range from collaborative, distributed mobile computing to disaster recovery(fire, flood, earthquake), law enforcement (crowd control, search and rescue) and digital battle field communication. Some key characteristics of these systems are team collaboration of large number of mobile units , limited bandwidth, the need for supporting multimedia real time traffic and low latency access to distributed resources(e.g., distributed database access for situation awareness in the battlefield).

Scalable and efficient routing scheme plays important role in ad-hoc networks. Existing wireless routing algorithms for ad-hoc networks can be classified into three general categories: precomputed global routing, on demand routing and flooding. In precomputed global routing schemes, routes to *all* destinations are periodically computed and maintained in the background. Precomputed global routing algorithms can be further divided into flat and hierarchical. In the flat routing category, every node has to maintain a routing table containing all the nodes in the network such as link state (LS), Destination-Sequence Distance Vector (DSDV) [20] based on Distributed Bellman-Ford (DBF) and WRP [16] based on a loop-free path-finding algorithm etc. These flat routing scheme can easily overload the channel capacity by sending nothing but large size periodical routing table updating messages among the nodes when the size of network becomes large.

Hierarchical techniques are commonly used in wired network for scalability [11, 13, 21, 24, 25]. For wireless networks, a hierarchical clustering and routing scheme based upon physical location management was recently proposed in [6, 12]. This scheme, however, creates implementation problems which are potentially complex to resolve. First, it does allocate Cluster IDs dynamically. This allocation must be unique - not an easy task in multi-hop mobile environment, where the hierarchical topology must be often reconfigured. Second, each cluster can dynamically merge and split, based on the number of nodes in the cluster. Frequent cluster changes may degrade the network performance significantly.

Another approach to scalability is On-demand routing. On-demand routing is the most recent entry in the class of wireless routing schemes. It is based on a query-reply approach. Examples include the Lightweight Mobile Routing (LMR) protocol [5], Ad-hoc On Demand Distance Vector Routing (AODV) [19], Temporally-Ordered Routing Algorithms (TORA) [18] [17], Dynamic Source Routing Protocol (DSR) [10] and ABR [23]. Typically, on-demand routing aims at providing solutions for networks with fast changing topologies. IETF's MANET working group is also focusing on the on-demand routing solution for an Ad Hoc Network Standard [19, 17, 10]. On-demand routing does scale well to large population as it does not regularly maintain a routing table for all destinations. Instead, as the name suggests, a route to a destination is computed only when there is a need. Thus, routing table storage is greatly reduced, if the traffic pattern is sparse. However, on-demand routing introduces the less desirable initial latency which makes it not very efficient for interactive traffic (e.g., distributed database query applications). It is also impossible to know in advance the quality of paths to all destinations (e.g., bandwidth, delay etc.) - a feature which can be very effective in call acceptance and path selection of QoS oriented connections.

Zone routing [8, 9] can be viewed an extension of on-demand routing, since it is based on a hybrid of on-demand routing and conventional routing . In fact, zone routing represents a first step towards hierarchical on-demand routing. For a routing inside of a the zone, any routing scheme, including Distributed Bellman-Ford (DBF) routing or Link State (LS) routing, can be applied. For a interzone routing, on-demand routing is used. The advantage of zone routing is its scalability, as it reduces the need for routing table storage. At the same time, the efficiency of global routing is preserved within each zone. However, for the interzone routing, the on-demand solution poses the usual problems of connection latency and QoS reporting.

In this paper, we will propose a new wireless hierarchical routing protocol (WHIRL). The key novelty is the notion of logical subnets (e.g., brigade in the battlefield, colleagues in the same organization, or a group of students from same class) in order to handle mobility. A group mobility model is described in section 2. In section 3 we explain the new hierarchical routing scheme in detail. The performance evaluation of our protocol is given in section 4. Section 5 concludes the paper.

2 Group Mobility Model

In a mobile wireless network, we can define two different categories of mobility models. One is the region based model mostly used in cellular radio networks. The other is the individual model which is suitable for ad-hoc wireless mobile networks.

The region based models deal with the movement across cells and the changes of aggregate traffic. Mobile hosts (MHs) generate new calls or hand-off calls, when they cross all boundaries, and have residual time in a cell. The movement of a host changes the traffic load. The emphasis of region mobility model is on the population density in a cell and the transit probability.

In an ad-hoc wireless mobile network, there are no base stations nor fixed cells. The models describe the individual motion behavior. There are various possible models in this class, which we briefly introduce below. The Random mobility model is widely used [15, 2, 22], while each node moves just randomly (e.g. Brownian model [2, 22]). The Markovian model is another good model for the random behavior of each mobile host with a transit state probability [3]. In these models, the motion of each mobile host is independent of the others.

In contrast, mobility models in which motions are dependent between ”mobility epochs” can also be defined. In these models, a mobile host’s previous motion behavior will affect the current in speed and/or direction [2, 22]. Some models set up some relationship among nodes. For instance, in a disaster situation, or a military deployment, mobile host movements are coordinated to achieve the same purpose. Examples include the Pursue model [22], where nodes are trying to move towards a target, and Column model [22], which represents a searching activity.

In an ad-hoc network, grouped motion behavior is very likely to occur. For example, in disaster recovery or military deployment, collaborative behavior among some nodes is quite common. A recently proposed group mobility model is the Exponential Correlated Random model [6]. Each group has a unique motion behavior, which is a function of its previous motion plus some random deviation. Nodes in each group follow the group moving trajectory. More precisely, they have their own motion pattern controlled by the same function as the group, but with personalized parameters. This model requires a parameter space for each node.

In the paper, we introduce our new group mobility model (Figure 1). Nodes are partitioned into groups based on their logical relationship. Each group has a center, whose motion represents the group's motion, including location, speed, and direction. The trajectory of a group can be predefined. The predefined trajectory can be a random-walk, or a target oriented path. Figure 1 gives out a two-group diagram. Each group has a group motion of vector $\overrightarrow{V_{g_i}}$ and has some geographic overlap. In our hierarchical routing scheme, groups represent logical subnets. Usually, nodes are uniformly distributed within the physical scope of a group. Each node has its random motion behavior, in addition to the group motion. Figure 1 illustrates this model. The movement of a node in Group g_1 between time tick τ and $\tau + 1$ is computed as follows. First, the reference location moves from $RP(\tau)$ to $RP(\tau + 1)$ with the group motion vector $\overrightarrow{GM}$. To this, a random motion vector $\overrightarrow{RM}$ is added. This random vector is independent from node's previous location.

A predefined route map is used to assign speed and direction to the group center and the mean motion displacement around each node's reference point.

3 Wireless Hierarchical Routing Protocol(WHIRL)

In a large, mobile network the problem of locating users and services by their names is not a trivial one. In a wired Internet the DNS provides a mapping between symbolic names and network addresses. The network address is then processed by the routing tables and leads directly to the destination. In wired networks with cellular radio extensions, Mobile IP was developed to handle the last hop indirection, from Home Agent to mobile user. In multihop wireless networks there is no fixed Home Agent. We propose the Wireless Hierarchical Routing Protocol (WHIRL) to attack this problem with a ”multihop extension” of the Mobile IP concept. We will distinguish between the ”physical” routing hierarchy, dictated by the geographical relationship between nodes, and the ”logical” hierarchy of subnets corresponding to members in the same group (e.g., tanks in the battlefield, or traveling salesman of the same company). We will keep track of logical subnets using a DNS hierarchy aimed at reducing control traffic O/H. Physical MAC layer clustering [7, 4] provides the first level of an efficient ”physical” routing hierarchy.

3.1 Overview

In WHIRL, the entire network is divided into logical subnets. Each subnet has one primary Home Agent (HA). It can have several secondary HAs from which, in the case of primary HA failure, a new primary HA will be selected . Each node has a *unique* identifier $NodeID$. The address of the node consists of two parts: logical $subnetID$ and $NodeID$, ie, $< subnetID >< NodeID >$. The $subnetID$ is used to identify the logical subnet to which each node belongs and the $NodeID$ is used in physical routing. In our study, we use the Link State (LS) physical routing scheme which is on the top of MAC layer clustering described in [7, 4] as the physical routing infrastructure for WHIRL. However, the concept of WHIRL can be built upon any routing scheme using $NodeID$ as the physical routing address. The key responsibility of the HA is to maintain the physical clustering information of its logical subnet members (see Table 3). HA also needs updates its own clustering information to all the cluster heads.

There are two phases in the WHIRL. The packet is routed first from the source to destination HA. Then it is routed from the destination HA to the final destination. The header of the packet contains the $NodeID$ of the destination cluster head $DestCH$. Initially, the $DestCH$ is set to $UNKNOWN$. The source sends the packet to its cluster head. The cluster head will look up its HA clustering table. The cluster head will set the $DestCH$ to be the $NodeID$ of the destination cluster head of the destination HA in the packet header according to the table. If the destination HA has more than one cluster heads, it will choose the one that has the minimum distance. All the intermediate gateways and cluster heads will route the packet according to the $DestCH$ in the packet header using the physical routing scheme. Once the destination cluster head gets the packet, it will send the packet to the HA. The HA scans its subnet member clustering table, finds out the cluster head $NodeID$ for the destination node and sets the $DestCH$ with it. The HA will then send the packet to its cluster head and the packet will be on the journey to its final destination cluster head. The destination cluster head will pass the the packet to destination node.

3.2 Cluster based physical routing

The WHIRL can be implemented on top of any physical routing scheme to achieve the scalability. We choose the LS based on the MAC clustering for our study. Cluster heads broadcast its neighbor cluster head list (Table 1) to all the other cluster heads periodically as well as the event triggering updates of neighbor cluster head. The LS routing protocol used here is a 2 level hierarchical LS routing among cluster heads, which is much more efficient than the flat conventional LS because only the cluster heads will broadcast the routing tables compare with flooding by every node in flat LS case.

Table 1: Format of neighbor cluster head list

Neighbor CH NodeID	Next Gateway	Sequence #

3.3 WHIRL logical subnet information

Each cluster head stores a HA clustering information table (Table 2). Each entry of the table contains the cluster head NodeID list of a HA. Each cluster head NodeID is associated with a timer. The cluster head piggybacks the cluster member addresses to the LS routing table updating packets. Recall the address of a node has both an unique physical ID and a logical subnet ID. If there is a HA in the cluster, the cluster head will mark the address of the HA. When a cluster head receives the update message from other cluster heads, it will add/update the Table 2 using the piggyback-ed member addresses by the sender. We use a timer for each cluster head in the list of each entry in the Table 2 to time out the stale entries. The timer will be refreshed whenever the cluster head receives a update for the HA. On the other hand, upon receiving a cluster member list from a cluster head, home agent will pick up its own members according to the subnet field of the address and update its member clustering information table (Table 3). We use soft state timer to time out obsolete subnet member entries.

Table 2: Format of HA cluster head NodeID list table

HA NodeID	(CH NodeID,Timer) List

Table 3: Format of logical subnet member cluster head NodeID list table

Member NodeID	(CH NodeID,Timer) List

3.4 WHIRL example

Figure 2 shows an example of WHIRL in multihop environment. Suppose node $Z.1$ wants to send a packet to node $A.9$. First node $Z.1$ sends this packet to its cluster head $Z.2$, $Z.2$ looks up its HA database table and finds out the cluster head of the destination HA ($A.7$) is 8. Then the $Z.2$ sets the $DestCH$ to be 8 and sends the packets to the next hop gateway from its routing table. The packet follows the physical routing until it reaches the HA $A.7$ via the $DestCH$ 8. HA $A.7$ will scan its member list to find out that the cluster head of the destination node $A.9$ is 10 and it reset the $DestCH$ to be 10. The packet will then be routed toward 10 and will reach node $A.9$ in the end. The details of the WHIRL are listed in appendix.

4 Performance Evaluation

4.1 Simulation Environment

This section describes the simulation environment of the performance measurements. We use a cluster infrastructure [7]. Within each cluster, the MAC protocol is selected so as to provide efficient transfer of packets between neighbor nodes. There are several options for MAC protocols, including IEEE 802.11, MACA (multiple Access Collision Avoidance) and FAMA (Floor Acquisition Multiple Access), which have been equipped with an RTS-CTS exchange to share the channel [14]. In our experiments we have selected polling. Namely, the cluster head polls the neighbor nodes to allocate the channel.

Polling was chosen here for several reasons. First, polling is consistent with the IEEE 802.11 standard access scheme (Point Coordination Function). Secondly, polling gives priority to the cluster head, which is desirable since only gateway nodes and cluster heads are involved in our hierarchical routing protocol. Third, polling permits easy support of real time connections (which can be scheduled at periodic intervals by the cluster head). Fourth, in our experiments each cluster has on average six neighbors (which is the optimal value in a uniform multihop architecture); thus polling latency is not a critical concern. For large cluster size the polling scheme can replaced by a polling/random access scheme, to reduce latency.

For the sake of simplicity we also assume that nodes (and in particular gateway nodes) can receive on multiple codes simultaneously (e.g., using multiple receivers). This property does not enhance communications within a cluster, since all wireless nodes are tuned to the same code anyway. It does, however, permit conflict free communications between clusters through gateway nodes.

The multihop, mobile wireless network simulator was developed using the parallel simulation language Maisie/PARSEC [1] and the simulator is very detailed. It models all the control message exchanges at the MAC layer (e.g., polling) and the network layer (Hierarchical Routing Protocol control messages). Thus, the simulator enables us to monitor the traffic O/H of the protocols. The network consists of 100 mobile hosts roaming in all directions at a predefined average speed in a 1000x1000 meter square. A reflecting boundary is assumed. Radio transmission range is 120 meters. Free space propagation channel model is assumed . Data rate is 2Mb/s. Packet length is 10 kbit for data, 2 kbit for cluster head neighboring list broadcast, and 500 bits for MAC control packets. Thus, transmission time is 5ms for data packet, 1 ms for neighboring list and 0.25 ms for control packet. Buffer size at each node is 15 packets.

4.2 Simulation Results

In this section we evaluate and compare the various routing schemes using the PARSEC simulation platform. The performance measures of interest in this study are: (a) impact of the group size of the group mobility model; (b) control O/H generated by the routing update mechanisms, and; (c) throughput. The variables are: number of pairs communicating with each other (the smaller the number, the more ”sparse” the traffic pattern) and node mobility.

Traffic load corresponds to an interactive environment. Several sessions are established (in most cases, 100 sessions) between different source/destination pairs. Within each session, data packets are generated following a Poisson process with average interval of 2.5 s. This amounts to a traffic volume of 4Kbps per source/destination pair, recalling that data packet length is 10 kbits. In all, this load (even with 500 pairs, which is the maximum we considered in our experiments) can be comfortably managed by the network in a static configuration, using any of the routing schemes so far described. With mobility, however, routes may become invalid, causing packets to be dropped and leading to throughput degradation.

In first experiment (Figure 3), we would like to find out the impact of the node mobility to the performance of WHIRL. We keep the logical subnet size fixed, i.e., 25 members each subnet and total 4 subnets and we vary the group size in the group mobility model (note: the size of the group in the group mobility is independent from the logical subnets). The number of groups in group mobility model can at most be equal to the number of the nodes. In this case, the group mobility model becomes individual node mobility model. The performance of WHIRL will degrade when the number of the group size increases. When the number of the groups increases, so does the randomness of the nodes mobility. WHIRL has the highest performance when the logical subnets are identical to the group in the group mobility model. WHIRL has the worst performance in the case of group member size is equal to 1 i.e., each individual node has its own independent mobility pattern. In the rest of the experiments, we use same mobility model for all the protocols that are compared, ie, the group size of the mobility model is 4 and the each group has 25 nodes.

In Figure 4, the throughput results are reported. Under the group mobility pattern of the logical subnets, the performance of WHIRL is better than DSDV and On Demand routing. DSDV's poor performance can be attributed to excessive channel usage by route control messages. Also, as mobility speed increases, more event-triggered updates are generated. In On Demand, when the number of pairs increases , the overhead of path finding increases.

The next experiment reports the control O/H caused by routing update messages in the various schemes (see Figure 5 and Figure 6). In Figure 5 we show the O/H as a function of number of communicating pairs, for a node speed of 60Km/hr. Tables are refreshed every 2 sec for DSDV and WHIRL, and are timed out after 1 sec for On Demand. The O/H is measured in Mbits/cluster. The O/H in DSDV and WHIRL is constant with number of pairs, as expected, since background updating is independent of user traffic. On Demand O/H, on the other hand, increases almost linearly with the number of pairs, up to 30 pairs (most of these pairs have distinct routes). Beyond 30 pairs, routes (or at least a large portion) are repeated and therefore the same route is reused by multiple sources to reach the same destination. Thus, the O/H increase is less than linear beyond 100 pairs since some path have already been discovered. Recalling that the maximum throughput achievable in a single cluster is 2 Mbps (ignoring MAC layer O/H), we note that both WHIRL and On Demand have acceptable O/H ($< 10\%$ in the entire range between 10 and 100 pairs). DSDV, on the other hand, is quite ”heavy”, introducing more than 50% of line overhead! This is because DSDV propagates full routing tables (with 100 entries). WHIRL uses much smaller tables (10 entries on average for clusterheads), while On Demand propagates only single entry tables whenever needed. It is clear that already at 100 nodes a flat routing scheme such as DSDV is untenable if the network is mobile and therefore requires rapid refresh.

In Figure 6 we report the control O/H as a function of node speed. On Demand O/H is constant since the updates are independent of speed. WHIRL and DSDV both exhibit increasing O/H with speed - update rate must be increased with speed to keep accurate routes. Again, DSDV O/H is prohibitive over the entire range between 20 and 90 Km/hr, while for On Demand and WHIRL, the penalty is quite reasonable.

Figure 7 and Figure 8 illustrate the tradeoffs between throughput and control O/H in WHIRL when the route refresh rate is varied. In Figure 7 (at 90 Km/hr) we note that the O/H increases linearly with refresh rate until the network becomes saturated with control packets, and starts dropping them. The throughput first increases rapidly with refresh rate, owing to more accurate routes and lower packet drops due to lack of route. Eventually, throughput peaks and then starts decreasing as the network becomes saturated and data packets are dropped because of buffer overflow. The optimum refresh rate is the rate yielding the max throughput value. Figure 8 reports the ”optimal” WHIRL refresh rate as a function of speed.

5 Conclusion

We have introduced the novel wireless hierarchical routing scheme WHIRL for large, mobile wireless networks with group mobility. The scheme is the extension of the conventional table driven routing schemes, but improves scalability by reducing update traffic O/H. WHIRL reduces the size of update messages by using a hierarchical addressing approach. It resolves the routing table scalability problem by using the hierarchical approach. For the applications that have the group mobility pattern, the WHIRL is the most appropriate scalable, low latency solution for the multihop ad hoc wireless network.

Compared with flat, table driven routing schemes (such as DSDV) the WHIRL exhibit a much better scalability, at the cost of routing inaccuracy and increased complexity (e.g., home agent). The scalability advantage is clearly shown by the simulation results.

We have also compared our scalable schemes with recently proposed On Demand routing schemes. Admittedly, WHIRL disadvantages with respect to On Demand routing, most notably: (a) if a route becomes invalid because of mobility, packets are dropped until the new route is establish via the background routing update process (in contrast, in On Demand, the packet is buffered until the new route is discovered); (b) protocol complexity is higher (e.g., home agent in WHIRL). On the other hand, WHIRL provides the following advantages: (a) lower latency for access to non frequently used destinations; (b) lower control traffic O/H in dense traffic situations (avoiding the flood type search for each destination); (c) QoS advertising prior to connection establishment (this is particularly useful for acceptance control in real time traffic environments)

Via simulation, we have compared WHIRL, DSDV and On Demand routing. We have explored only a small set of the properties and tradeoffs. Yet, the simulation results clearly indicate the inadequacy of flat, table driven routing as the number of nodes grows. Also, clear is the increase of On Demand control overhead as the number of connections grows (i.e., the traffic pattern becomes dense).

In summary, WHIRL is a scalable routing protocol for the applications that has group mobility. A promising direction of future research is the integration of hierarchical, table driven concepts with on demand routing concepts to generate routing strategies that can perform consistently well across various application domains.

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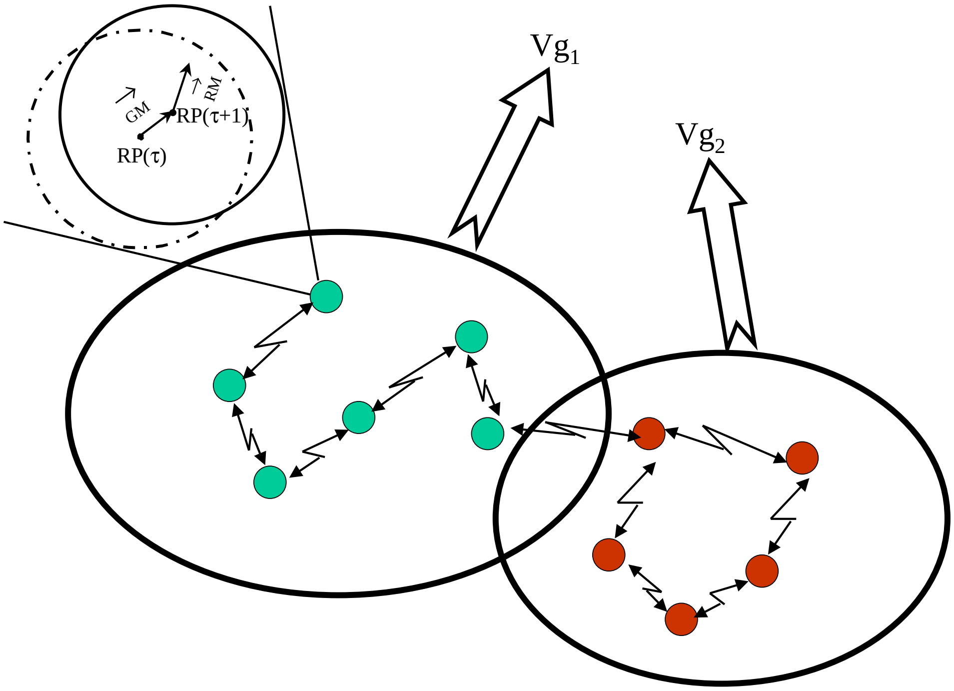

Figure 1: Group Mobility Model

A WHIRL Protocol

```
proc NodeWHIRL ≡
  if $pkt.destination \in \{Neighbour\}$
    then SendPkt(pkt.destination);
     else if $node.ClusterStatus = Ordinary$
            then OrdinaryNode();
             else if $node.ClusterStatus = ClusterHead$
                    then ClusterHeadNode();
                     else /*Gateway node */
                          GatewayNode();
                 fi
          fi
  fi
.
proc ClusterHeadNode() ≡
  if $pkt.DestCH = UNKNOWN$
    then if $node = HomeAgentOfDestination$
            then $pkt.DestCH \leftarrow Destination.ClusterHead$;
             else
                 $pkt.DestCH \leftarrow HomeAgentOfDestination.ClusterHead$;
         fi
         SendPkt(NextGateway(pkt.DestCH));
     else
         if $node = pkt.DestCH$
           then
                 if $node = HomeAgentOfDestination$
                   then $pkt.DestCH \leftarrow Destination.ClusterHead$;
                        SendPkt(NextGateway(pkt.DestCH));
                    else if $HomeAgentOfDestination \in \{Neighbour\}$
                           then SendPkt(HomeAgentOfDestination);
                            else
                                ErrorHandler;
                        fi
                 fi
            else
                 SendPkt(NextGateway(pkt.DestCH));
         fi
  fi
.
```

```
proc GatewayNode() ≡
  if $pkt.DestCH = UNKNOWN$
    then if $node = HomeAgentOfDestination$
            then $pkt.DestCH \leftarrow Destination.ClusterHead$;
             else
                 $pkt.DestCH \leftarrow HomeAgentOfDestination.ClusterHead$;
         fi
         SendPkt(NextClusterHead(pkt.DestCH));
     else
         if $node = HomeAgentOfDestination$
            $pkt.DestCH \leftarrow Destination.ClusterHead$;
         fi
         SendPkt(NextClusterHead(pkt.DestCH));
  fi
.
proc OrdinaryNode() ≡
  if $node \neq HomeAgentOfDestination$
    then SendPkt(node.ClusterHead);
     else
         $pkt.DestCH \leftarrow Destination.ClusterHead$;
         SendPkt(node.ClusterHead);
  fi
.
```

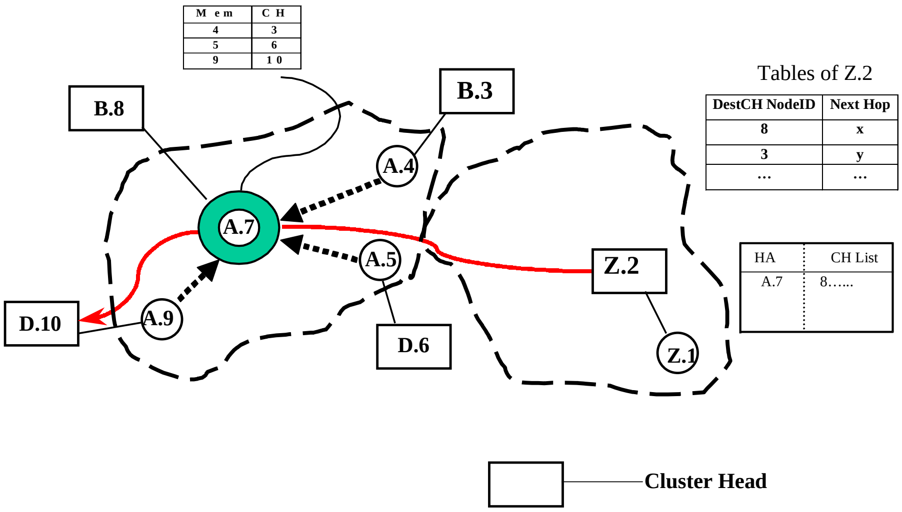

Figure 2: WHIRL routing example

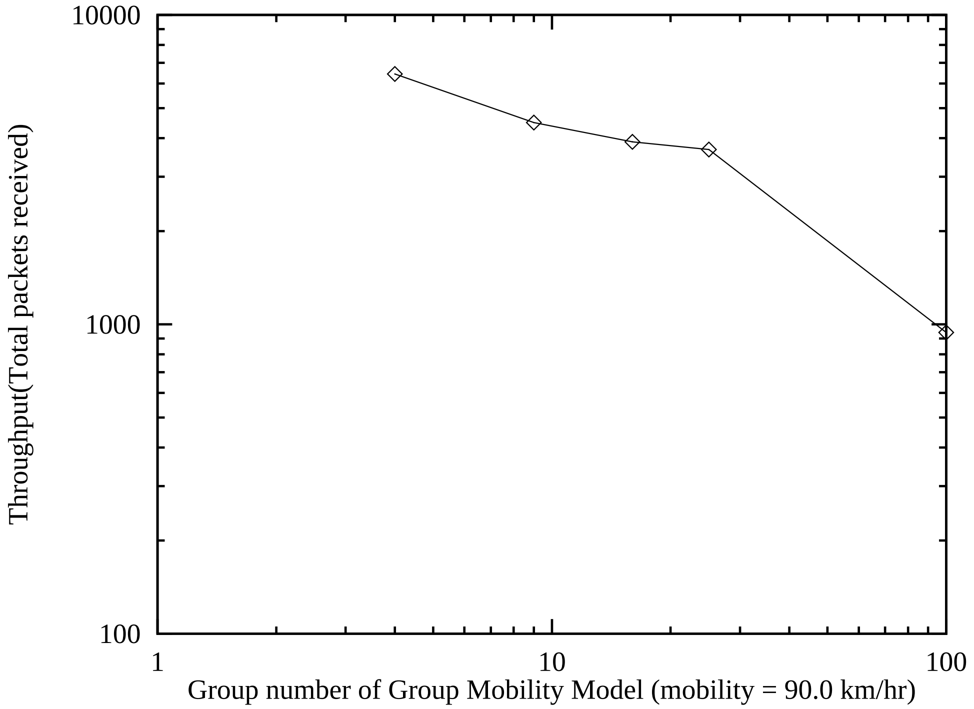

Figure 3: Throughput vs group number (mobility = 90 km/hr)

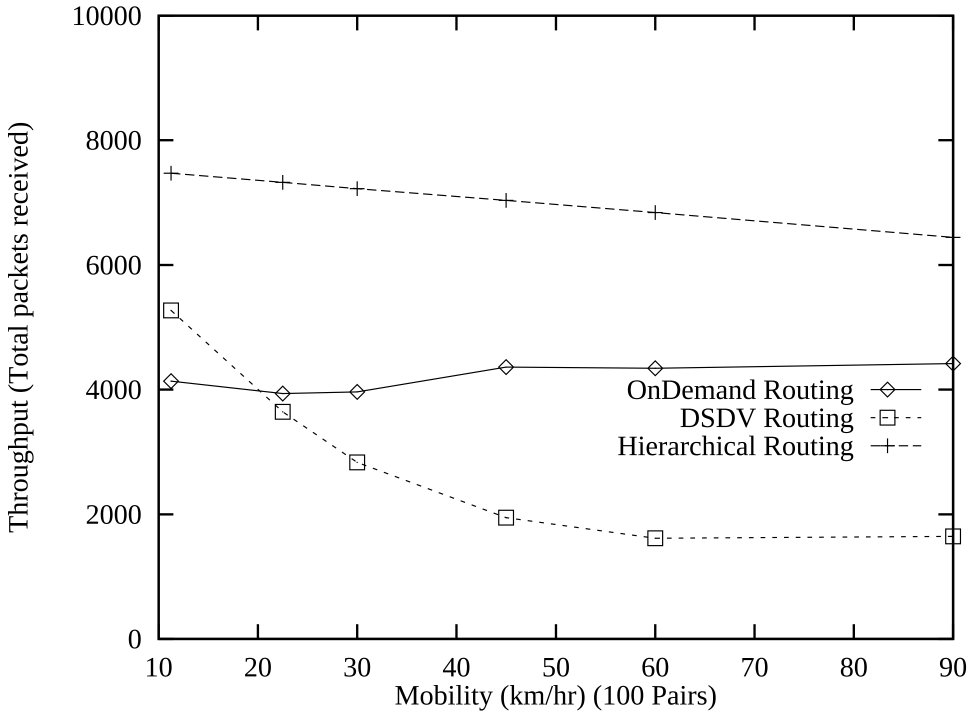

Figure 4: Throughput vs. Mobility (100 Pairs)

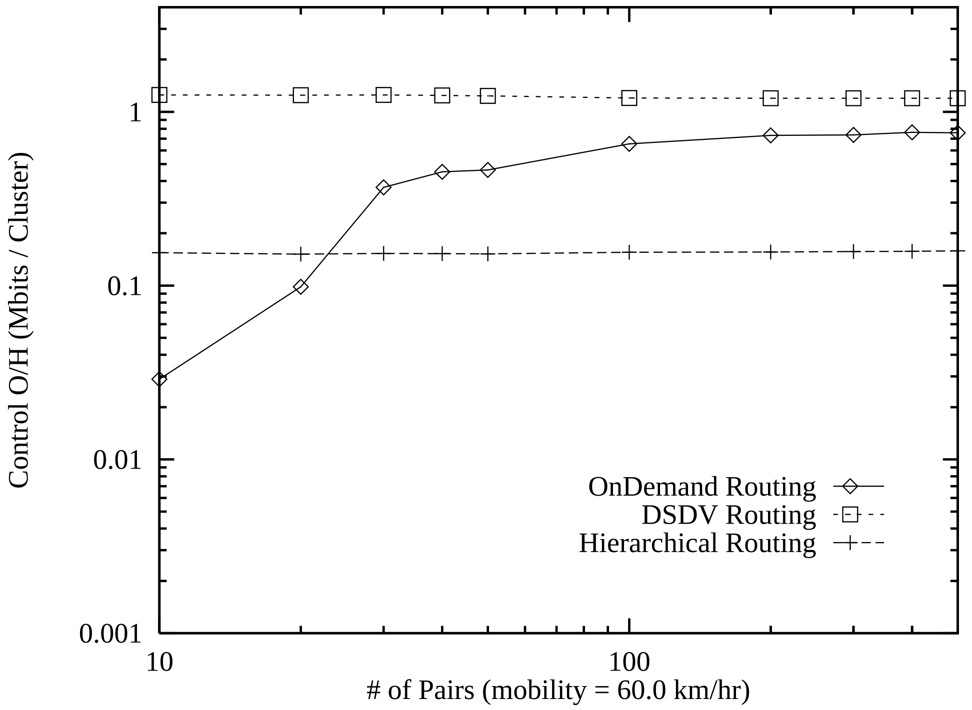

Figure 5: Control O/H vs. Traffic Pairs

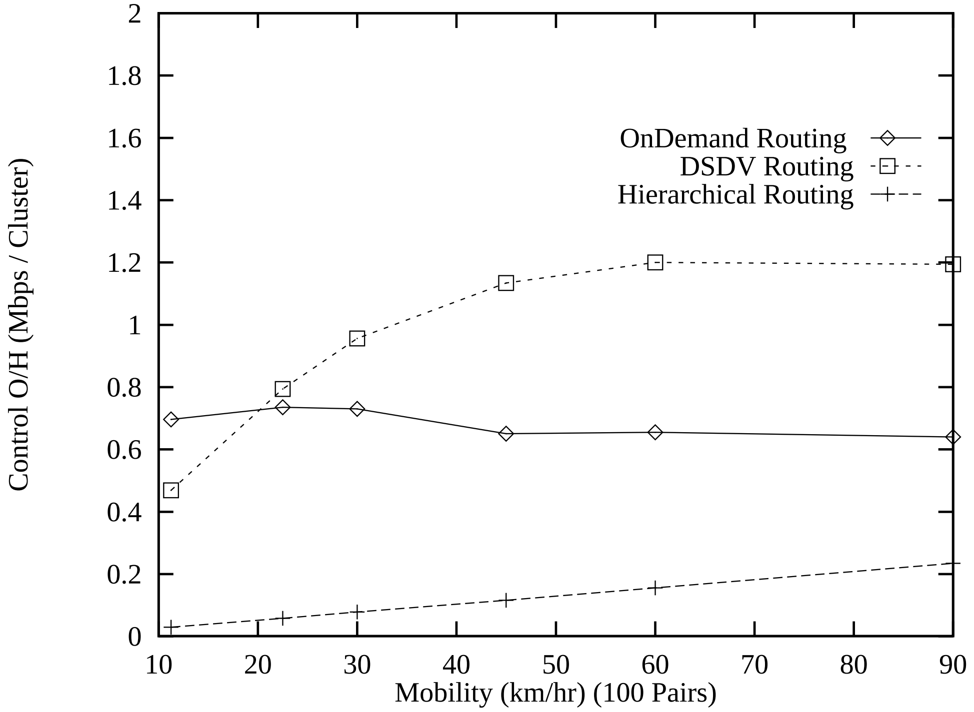

Figure 6: Control O/H vs. Mobility (100 Pairs)

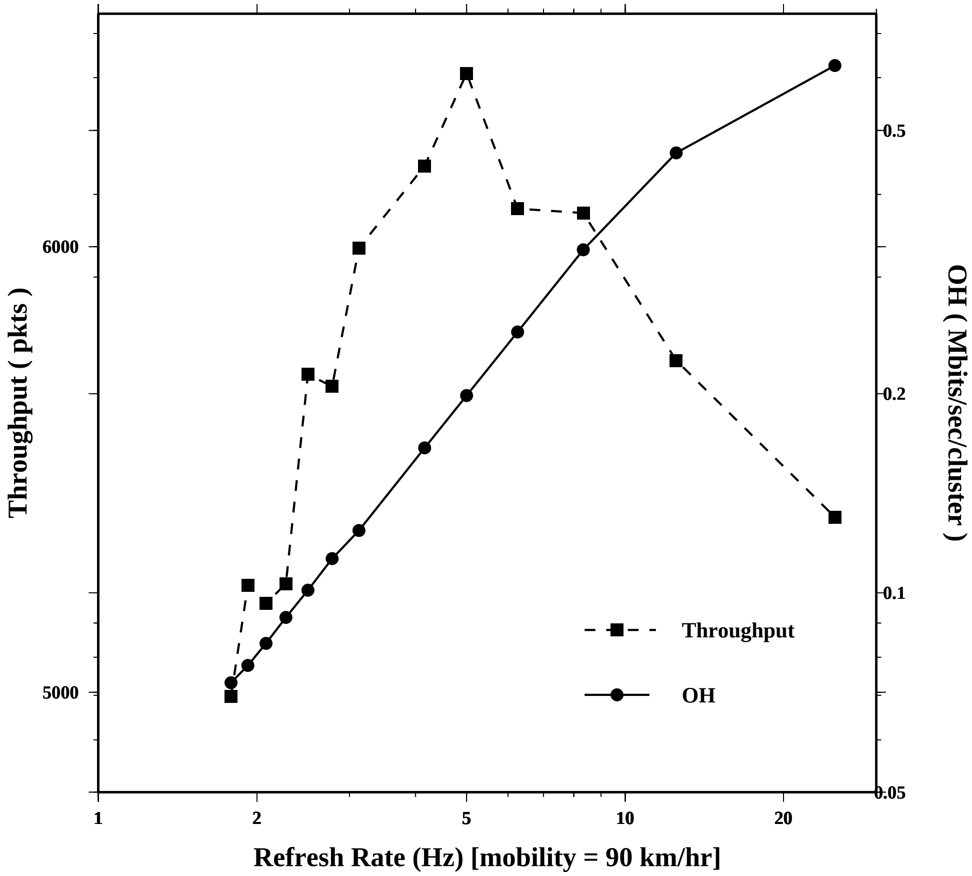

Figure 7: Soft state evaluation (90 km/hr)

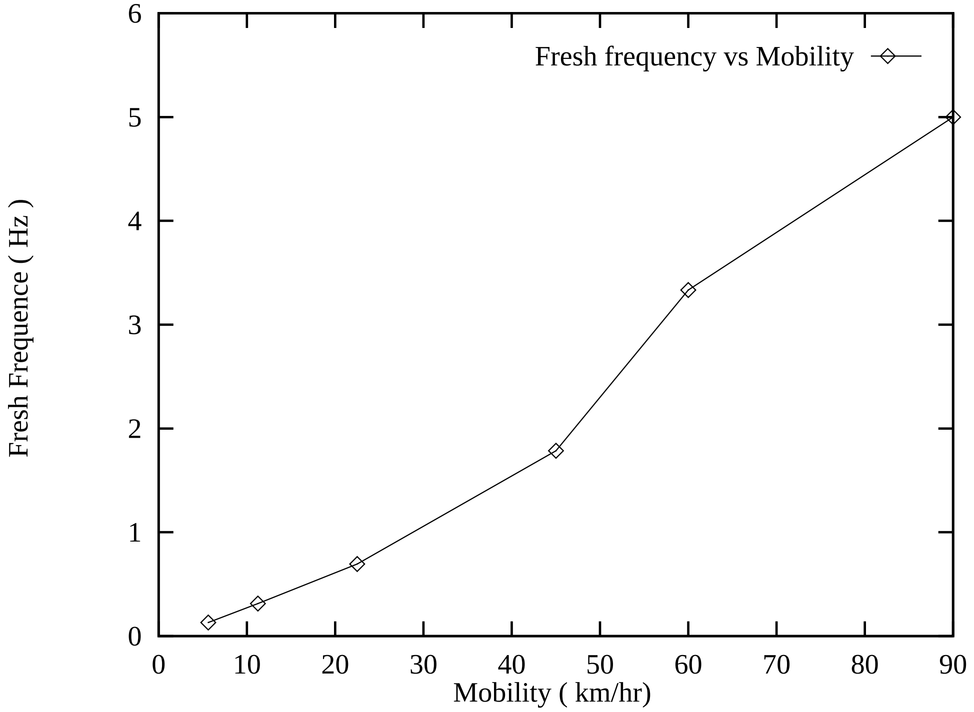

Figure 8: Refresh Rate vs Mobility