A Novel Distributed Routing Protocol To Support Ad-Hoc Mobile Computing

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Abstract

This paper presents a new, simple and bandwidth-efficient distributed routing protocol for ad-hoc mobile networks. Unlike the conventional distributed routing algorithms, our protocol does not attempt to consistently maintain routing information in every nodes. In an ad-hoc mobile network where mobile hosts are acting as routers and where routes are made inconsistent by mobile hosts movement, we employ a new associativity-based routing scheme where a route is selected based on nodes having associativity states that imply periods of stability. In this manner, the routes selected are likely to be long-lived and hence there is no need to restart frequently, resulting in higher attainable throughput. The association property also allows the integration of ad-hoc routing into a BS-oriented Wireless LAN environment, providing the fault tolerance in times of base stations (BSs) failures. The protocol is free from loops, deadlock and packet duplicates and has scalable memory requirements. Simulation results obtained reveal that shorter and better routes can be discovered during route re-constructions.

1 Introduction

1.1 The Problem & Motivation

Unlike infra-structured Wireless LANs (WLANs) with base stations (BSs) providing coverage for mobile hosts (MHs), ad-hoc mobile networks do not have any access to BSs. The problem here relates to how MHs can communicate with one other, over the wireless media, without any support from infra-structured network components. The most obvious problem is to devise a scheme to compute route which could adapt well to link changes. Conventional distributed routing schemes attempt to maintain consistent routing information by performing periodic link and topology updates. These, however, are undesirable for MHs in an ad-hoc mobile network since MHs migrations cause frequent link changes, which result in enormous transmissions over the wireless media to propagate and update routes. This is very inefficient in an environment where radio bandwidth and battery power are regarded as scarce resources. Hence, there is a need for a new, efficient and robust routing scheme for MHs in an ad-hoc mobile network.

1.2 Ad-Hoc Mobile Routing Schemes

The ARPANET Packet Radio Network (PRN) [R. 78] [Wes87] is the earliest deployment of a regional-wide wireless data network. In a PRN, all components (repeaters, terminals and stations) can be mobile. The approaches to routing and packet forwarding in PRNs are used here as the basis for ad-hoc mobile routing and consequently they are briefly described below.

1.2.1 Routing in PRNs

In 'point-to-point' routing, the station computes all the routing information and the decision is either distributed to the repeaters involved in the route or to the source packet radio. This scheme was found to be suitable for slow moving user terminals. However, in 'broadcast routing', each packet radiates away from the source packet radio with a wave-front like propagation. Since no station needs to be present to compute routes, the destination address serves to identify the intended recipient. For fast moving user terminals, broadcast routing was found to be useful as it avoids the need to process rapidly changing routes.

1.2.2 Packet Forwarding in PRNs

The connectionless approach to routing requires some background operation to maintain up-to-date network topology and link information in each node. This means that as topology changes, the background routing traffic can be substantial. This is commonly associated with broadcast routing, where each packet carries sufficient routing information for it to arrive at the destination. However, in the connection-oriented approach, an explicit route establishment phase is required before data traffic

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can be transported. This approach is commonly associated with point-to-point routing, where each node in a route has a lookup table for forwarding incoming packets to the respective out-going links. Hence, if a topology changes, a route re-establishment phase is needed. Detailed comparisons between these approaches are found in [B. 87].

1.2.3 Current Ad-Hoc Mobile Routing Schemes

Existing ad-hoc mobile routing schemes are based on either broadcast or point-to-point routing using either a connectionless or connection-oriented packet forwarding approach. We briefly describe three such schemes.

Cluster-based routing [P. 95], in essence, uses the broadcast routing and connectionless packet forwarding approach. It relies on existing routing scheme such as link-state or distance-vector routing to derive network topology and link information. On top of this, a clustering methodology is used to reduce the amount of updates due to MHs migrations. Routes are constructed between all pairs of nodes and route maintenance is essentially cluster maintenance. Hence this method is inefficient.

In source-initiated distributed routing [Eph95], however, a combination of point-to-point and broadcast routing using the connection-oriented packet forwarding approach is used. Here, routes are initiated by the source and are constructed based on demand. Hence this scheme forgoes the need to constantly propagate up-to-date routing information throughout the network. However, because alternate route information is used during route re-construction (RRC), problems of stale routes exist.

Finally, for destination sequence distance-vector (DSDV) routing [Bha94], enhancement to the existing distance-vector Bellman-Ford routing is made in order to support ad-hoc MHs. Because each MH has to periodically advertises its view of the network topology, this scheme is inefficient. Similar to cluster-based routing, this scheme uses the broadcast routing and connectionless packet forwarding approach.

Hence, the problems associated with the existing schemes motivate us to seek a better routing approach to support ah-hoc mobile computing. This paper is organised as follows. Section 2 introduces the new concept of associativity-based routing (ABR). A detailed description of the ABR protocol is then presented in Section 3.

2 Associativity-Based Routing

Our proposed routing scheme is a compromise between broadcast and point-to-point routing. Similar to [Eph95], we only maintain routes for sources that actually desire routes. However, we do not employ RRC based on alternate routes information existing in intermediate nodes (INs), therefore avoiding stale routes. In addition, route decision is performed at the destination node and only the best selected route will be valid while all other possible routes remain passive. This therefore avoid packet duplicates. Furthermore, the selected route tends to be more long-lived due to the property of associativity, which is described below.

2.1 Principles of ABR

The essence of ABR lies on the fact that a MH's association with its neighbour changes as it is migrating and its transiting period can be identified by the associativity "ticks". The migration is such that after this unstable period, there exists a period of stability, where the MH will spend some dormant time within a cell before it starts to move again[1]. The threshold where the associativity transitions take place is defined by $A_{threshold}$, as shown in Figure 1.

Associativity ticks are updated by the MH's data link layer protocol, which periodically broadcasts beacons identifying itself and constantly updates its associativity ticks in accordance to the MHs sighted in its neighbourhood. In a scenario where an ad-hoc WLAN has a wireless cell size of 10 m with a MH's minimum migration speed of 2 m/s and a beacon transmission interval of a second, the maximum possible associativity ticks of the migrating MH with its neighbours is 5. Likewise, the neighbouring MHs will also record associativity ticks of no more than 5. This value is $A_{threshold}$ and any associativity ticks greater than $A_{threshold}$ implies periods of association stability.

To further support our claim about 'dormant time', we gathered the mobility traces of 52 badge wearers for a consecutive of 5 days at the Cambridge University Computer Laboratory[2] from the Active Badge System [Hop92]. The traces provide specific information on the sighted location, the wireless cell, the MH, the quality of sightings and the time of sightings. Figure 2 and 3 show the dormant time distributions obtained for a day and a week respectively. The average dormant time ranges from 35.79 to 47.99 minutes. Hence, we believe that a practical mobile user will spend some dormant time at a location before he/she decides to move again.

2.2 Properties of ABR

A MH is said to exhibit high state of mobility when it has low associativity ticks with its neighbours. On the other hand, if high associativity ticks are observed, then the MH is in the stability state and this is the ideal point to select the MH to perform ad-hoc routing. Hence, if all the MHs in a route path have high associativity ticks, an inter-locking phenomenon arises where "my" degree of associativity ticks will be high if "you" do not move out of reachability and are in stable state. The associativity ticks are reset when the neighbours or the MH itself moves out of proximity, not when the communication session is completed.

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[1] Refers to moves causing link changes with the MH's neighbours.

[2] Details available from http://www.cl.cam.ac.uk/

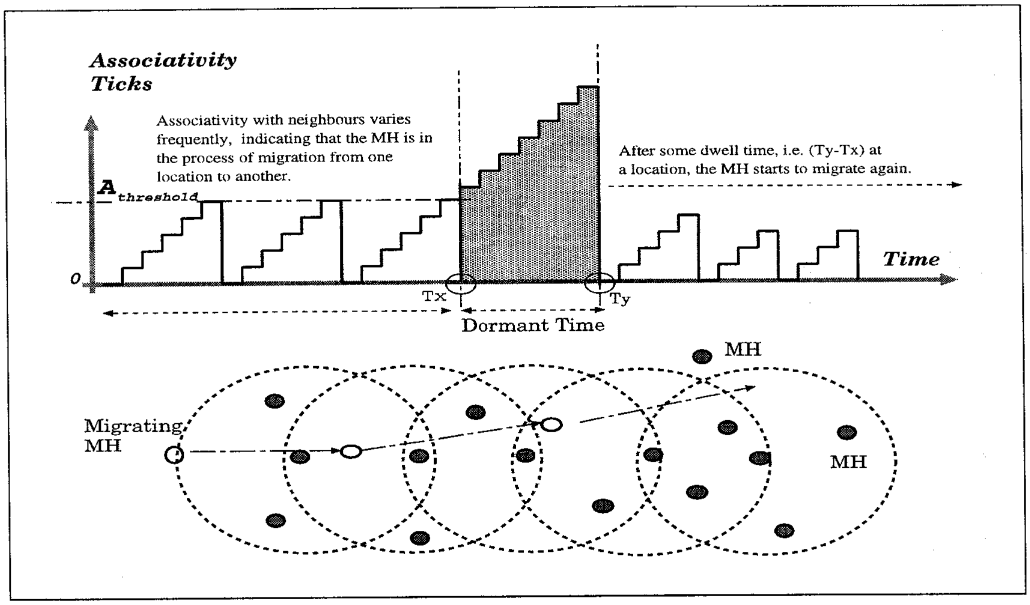

Figure 1: Time & Spatial Representations of Associativity of a MH with its Neighbours.

2.3 Applicability To BS-Oriented Wireless LANs

The properties of associativity can also be applied to BS-oriented WLANs. When a MH 'sees' a BS, its associativity ticks with the BS will be high. But this associativity ticks will be reset when the BS fails (equivalent to an associated node moving away). Hence, under such circumstances, the MH can apply associativity-based ad-hoc routing to re-route its packets to its neighbouring MHs who may have access to other BSs. In this manner, robustness can be achieved during BSs failures.

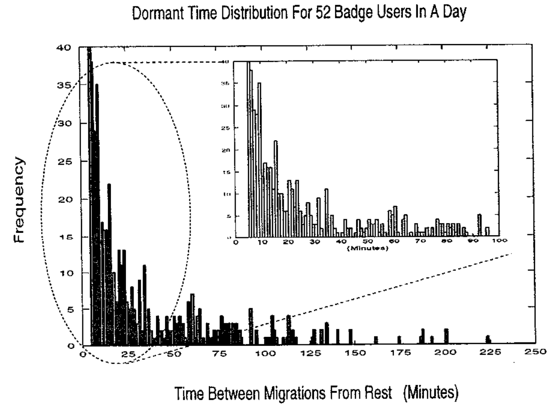

Figure 2: Dormant Time Distribution of 52 Badge Wearers on a day at the Computer Laboratory.

2.4 New Routing Metrics

Conventional mobile routing qualities are characterised by (a) fast adaptability to link changes, (b) minimum hop path to destination, (c) propagation delay, (d) loop avoidance, etc. Some existing protocols go to the extreme of frequent broadcasts in order to attain fast route convergence at the expense of excessive radio bandwidth consumption, which is undesirable. We identify the following new routing metrics : (a) longevity of a route and (b) relaying load of INs supporting existing routes. The 'longevity' of a route is important as shorter but short-lived route will result in frequent data flow interruptions and RRCs. In addition, even routing load distribution is important as no one particular MH should be unfairly burdened to support many packet-relaying functions. This also alleviates the possibility of network congestion.

Dormant Time (Minutes)					
Distributions	Day of the Week				
	Mon	Tue	Wed	Thur	Fri
Maximum	299.15	277.00	281.68	223.06	297.64
Minimum	5.08	5.06	5.10	5.01	5.02
Mean	35.79	36.26	41.08	40.84	47.99
Standard Deviation	46.63	50.88	50.55	55.40	62.81

Figure 3: Dormant Time Distribution of 52 Badge Wearers in a week at the Computer Laboratory.

Table 1 : ABR Route Selection Algorithm

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Let $S_i$ be the set of possible routes from SRC→DEST,
where $i = 1, 2, \ldots$
Let $RL^i_j$ be the relaying load in each node j of a route in $S_i$,
where $j = 1, 2, \ldots$
Let $RL_{max}$ be the maximum route relaying load allowed per MH.
Let $AT_{threshold}$ be the minimum associativity ticks needed for
association stability.
Let $AT^i_j$ the associativity ticks in each node j of a route in $S_i$."
Let $H_i$ be the aggregate degree of association stability of a route in $S_i$.
Let $L_i$ be the aggregate degree of association instability of a route in $S_i$.
Let $H_{i_{ave}}$ be the average degree of association stability of a route in $S_i$.
Let $L_{i_{ave}}$ be the average degree of association instability of a route in $S_i$.
Let $Y_i$ be the no. of nodes of a route in $S_i$ having acceptable relaying load.
Let $U_i$ be the no. of nodes of a route in $S_i$ having unacceptable relaying load.
Let $Y_{i_{ave}}$ be the average acceptable relaying load factor.
Let $U_{i_{ave}}$ be the average unacceptable relaying load factor.

Begin
    For each route $i$ in $S_i$
    Begin
    $a \leftarrow 0$
        For each node j in route $S_i$
        Begin
            If ($AT^i_j \geq AT_{threshold}$) $H_i$++ ;
                else $L_i$ ++;
            If ($RL^i_j \geq RL_{max}$) $U_i$++;
                else $Y_i$ ++;
            a ++;
        End
        $H_{i_{ave}} = H_i/a$; $L_{i_{ave}} = L_i/a$;
        $U_{i_{ave}} = U_i/a$; $Y_{i_{ave}} = Y_i/a$;
    End

    Best Route Computation
    Let the set of acceptable routes with $U_{i_{ave}} = 0$ and $H_{i_{ave}} \neq 0$ be $P_l$,
    where $P_l \subseteq S_i$
     Begin
        * Find Route With Highest Degree of Association Stability *
         Compute a route $k$ with $H_{k_{ave}} > H_{l_{ave}}$, $\forall$ $l \neq k$.
         or if a set of routes $K_n$ exists such that
        $H_{K1_{ave}} = H_{K2_{ave}} \ldots = H_{Kp_{ave}}$, where $n$ = {1,2,3,...,p}
           Begin
           * Compute Minimum Hop Route Without Violating Relaying Load *
            Compute a route $K_k$ with $Min\{K_k\} < Min\{K_m\}, \forall$ $m \neq k$.
            or if a set of routes $K_o$ exists such that
            $Min\{K_1\} = Min\{K_2\} \ldots = Min\{K_q\}$,
            where $o$={1,2,3,...,q}
              Begin
              * Multiple Same Associativity & Minimum-Hop Routes Exists *
               Arbitrarily select a minimum-hop route $K_k$ from $K_o$
              End
           End
     End
End
```

2.5 ABR Route Selection Rules

Given a set of possible routes from the source (SRC) to the destination node (DEST), the best route must be computed based on the degree of association stability, route relaying load and shorter paths. The route selection algorithm is formally stated in Table 1.

3 ABR Protocol Description

The associativity-based routing protocol consists of two phases, namely : (a) route discovery phase and (b) route re-construction (RRC) phase. Initially when a source node desires a route, the route discovery phase is invoked. When the link of an established route changes due to SRC, DEST, INs or subnet-bridging MHs migrations, the RRC phase is invoked. These two phases will be discussed below and a summary of the routing protocol is presented in Table 2.

3.1 ABR Route Discovery Phase

The route discovery phase comprises of a broadcast query and await-reply (BQ-REPLY) cycle.

3.1.1 BQ-REPLY Cycle

Initially, all nodes except those of DEST's neighbours have no routes to the DEST. A node desiring a route broadcasts a BQ message, in search of MHs which have a route to the DEST. Here, no BQ packet will be broadcast more than once.

All INs that receive the query will check if it has previously processed the packet. If affirmative, the query packet will be discarded, otherwise the node will check if it is the DEST. If it is not the DEST, the IN appends its MH address at the IN IDs field of the query packet and broadcast it to its neighbours (if it has any). The associativity ticks with its neighbours will also be appended, along with all the other routing metrics.

The next succeeding IN will then erase its upstream node neighbours' associativity ticks entries and retain only those concerned with itself and its upstream node. In this manner, the query packet reaching the DEST will only contain the intermediate MHs' addresses and their associativity ticks, along with the route relaying load, propagation delays and hop count information. The resulting BQ packet is variable in length and has the following format :

TYPE	SRC ID	DEST ID	LIVE	IN IDs	METRICS	SEQ NO.	CRC

BQ Control Packet

The DEST will, at an appropriate time after receiving the first BQ packet, know all the possible routes and their qualities. It can then select the best route and send a REPLY packet back to the SRC. This causes the INs in the route to mark its route to the DEST as valid and hence all other possible routes will be inactive and will not relay packets destined for the DEST, even if they hear the transmission. This therefore avoids **duplicated packets** from arriving at the DEST. The REPLY packet also contains a summary of the selected route metrics. The REPLY packet is variable in length and its format is shown below :

TYPE	SRC ID	DEST ID	IN IDs	SEQ NO.	ROUTE QUALITIES	CRC

REPLY Control Packet

3.2 ABR Route Re-Construction Phase

The route maintenance phase performs the following operations : (a) partial route discovery, (b) invalid route

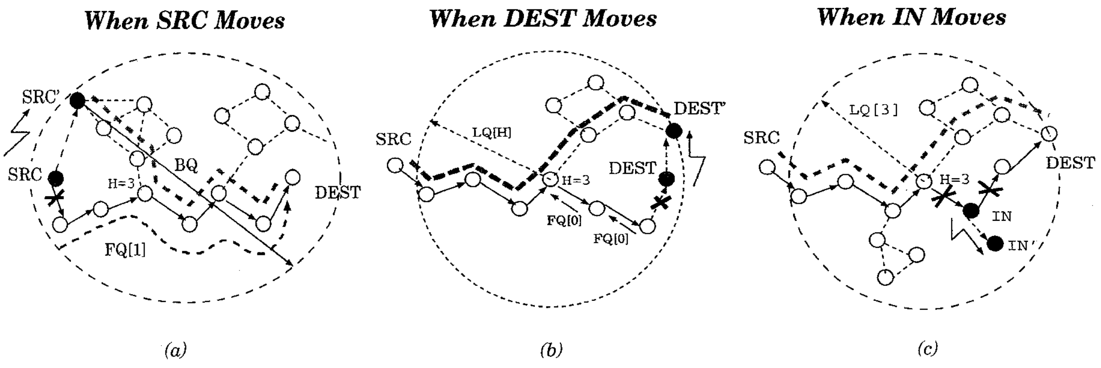

Figure 4: Route Maintenance when SRC, DEST and IN moves.

erasure (c) valid route update and (d) new route discovery (worst case). These operations may be invoked by different types of MH movements. Before concurrent MHs movements are analysed, we first examine the consequences of individual node's movements. The following narrations shall refer to Figures 4a, b and c respectively.

3.2.1 SRC Node Movement

Since the routing protocol is source-initiated, any moves by the SRC will invoke a RRC process equivalent to that of a route initialisation, i.e. via a BQ_REPLY process. It will be shown later that this avoids "multiple-RRCs" conflicts as a result of concurrent nodes' movements.

3.2.2 DEST Node Movement

When the DEST moves, the DEST's immediate upstream neighbour (i.e. the pivoting node) will erase its route. This is followed by a LQ{H} process to ascertain if the DEST is still reachable. 'H' here refers to the hop count from the upstream node to the DEST. If the DEST receives the LQ packets, it will select the best partial route and send a REPLY, otherwise the LQ_TIMEOUT period will be reached and the pivoting node will backtrack to the next upstream node.

During the backtrack, the new pivoting node will erase the route through that link and perform a LQ{H} process until the new pivoting node is greater than half $Hop_{src-dest}$ away from the DEST or when a new partial route is found. If no partial route is found, the pivoting node will send a $FQ[1]$ packet back to the SRC to initiate a BQ process. The formats of the FQ and LQ packets are shown below. The ORG ID is the pivoting node ID while the SRC and DEST IDs identify the route. STEP=0 in the FQ control packet means that backtracking is to be performed one hop at a time (in the upstream direction) while a STEP=1 implies that the FQ packet will be propagated straight back to the SRC to invoke the BQ process or to the DEST to erase invalid routes. The DIR flag serves to indicate the direction of FQ{1} propagation.

TYPE	ORG ID	SRC ID	DEST ID	SEQ NO.	STEP	DIR	CRC

FQ Control Packet

TYPE	SRC ID	DEST ID	IN IDs	METRICS	SEQ NO.	LIVE	CRC

LQ Control Packet

3.2.3 Intermediate Nodes (INs) Movements

- **Upper Arm INs' Moves**

  The 'upper arm' of a route refers to the INs and the DEST that contribute to half the route length from SRC to DEST. When any IN moves, its immediate upstream node removes its outgoing node entry and its immediate downstream neighbour propagates a FQ{1} packet towards the DEST, thereby deleting all the subsequent downstream nodes' routing tables (RTs) entries.

  A LQ{H} process is then invoked by the pivoting node to locate alternate partial routes. The DEST, on receiving multiple LQs, selects the best partial route and returns a REPLY to the pivoting node. This causes all INs between DEST and the pivoting node to update their RTs. On receiving the REPLY, the pivoting node updates its RT and appends the outgoing node ID into the data packet. This ensures that only one partial route is selected.

  As before, if the pivoting node is X hops away from the DEST via the previous active route, then $H = X$ will be used in the hope that during the LQ{H} process, the DEST is still within X hops range or shorter.

This therefore attempts to rebuild partial paths of equal or shorter lengths (i.e. **route optimisation** during RRCs).

However, if no partial route exists, LQ_TIMEOUT will expire and a FQ{0} packet will be sent by the pivoting node to the next upstream node, and the cycle repeats until the next pivoting node has a hop count greater than half $Hop_{src-dest}$ or when a new partial route to the DEST is found.

- **Lower Arm INs' Moves**

  The 'lower arm' refers to the SRC and INs that contribute to half the route length from SRC to DEST. If any of these nodes moves, $FQ[1]$ packet will be propagated downstream towards the DEST, and the pivoting node will perform LQ{H} and await for the DEST's REPLY. If no REPLY is received, FQ[0] packet is sent to the next upstream node and the new pivoting node then invokes the LQ{H} process again, but with a different value of H. The cycle proceeds until the new pivoting node is the SRC, where the BQ process will be initiated to discover a new route.

3.2.4 Subnet-Bridging MH Movement

The migration of a subnet-bridging MH beyond the radio coverage of its neighbouring MHs will cause the mobile subnet to be partitioned. If an existing route does not span across the fragmented subnets, the route is not affected. Otherwise, i.e. the subnet-bridging MH is an IN of the route, the route is invalidated as the DEST is no longer reachable, despite any LQ or BQ attempts. In such instances, the LQ_FQ cycle will eventually inform the SRC about the partitioning and the SRC can then invoke BQ query several times or it can inform the mobile user and prompt him to try later.

3.2.5 Concurrent Nodes Movements

Race conditions exist due to multiple invocations of RRC processes as a result of concurrent movements by SRC, DEST and INs. The following explains why the proposed routing protocol is immune to 'multiple-RRCs' conflicts.

- **DEST-Moves RRC Interrupted By Upstream INs' Moves**

  When the DEST moves and while the RRC is in progress, any upstream INs moves will cause their respective downstream neighbours' route to be deleted. The new pivoting node nearest to the SRC will perform the RRC and all other RRCs will be passive when they hear the newer LQ broadcast for the same route. Hence, only one RRC is valid.

- **Upper-Arm IN RRC Interrupted By Lower Arm INs' Moves**

  This is the same as the above-mentioned case. Note that the same argument can be applied to the case when a LQ process has to be aborted and a FQ[1] packet has to be sent to the SRC to invoke a BQ but is hindered due to some upstream IN movements. The new pivoting node nearest to the SRC will swamp the earlier RRC processes by invoking a new LQ.

- **Lower-Arm IN RRC Interrupted By Upper Arm INs' Moves**

  While a lower arm IN RRC is taking place, any movements by any upper arm INs will not result in LQ[H] or FQ[1] process being initiated since the lower arm IN has earlier sent FQ[1] downstream to erase invalid routes. If the FQ[1] packet does not succeed in propagating towards the DEST, the LQ[H] process initiated by the lower arm IN will also serve to delete these invalid routes.

- **Lower/Upper-Arm IN RRC Interrupted By DEST's Moves**

  This has no effect on the RRC, as the LQ[H] process uses a localised query approach to locate the DEST. Once the DEST is in its stable state and is reachable to the pivoting node, the RRC will be successful.

- **Lower/Upper-Arm IN RRC Interrupted By SRC's Moves**

  While lower or upper arm IN RRC is in progress, any moves by the SRC will result in a BQ, which will swamp out all on-going LQ_REPLY_FQ processes related to that route. Hence, unfruitful and stale RRCs will not continue and a new route has to be discovered via the BQ process.

- **SRC and DEST Nodes Moving Away from INs**

  When this occurs, RRCs as a result of DEST and SRC moves will be initiated. However, the BQ process initiated by the SRC will again swamp out all unnecessary on-going RRCs.

- **DEST Migrating Into SRC's Radio Coverage Range**

  When the DEST migrates, RRC is achieved via the $LQ[H]$ process. However, when the DEST is within the SRC's coverage range, packet duplicates will result since the DEST now receives packets from the SRC directly and also from the original SRC-DEST route. Hence, to avoid cell duplicates and non-optimal routes, the SRC, on discovering that the DEST is within range and is in stable state, will send FQ{1} packet downstream to erase existing route and to re-establish a new single-hop route with the DEST.

Associativity Valid	Associativity Violated					
	INs & DEST Moves		SRC Moves	Subnet Bridging MH Moves		Concurrent Moves
	Normal Case	Worst Case		Route Within Subnet	Route Spans Across Subnets	
No Route Re-Constructions Are Needed	LQ, REPLY Cycle Success	BQ, REPLY Cycle Success	BQ, REPLY Cycle Success	No Route Re-Constructions Are Needed	Network is Partitioned. BQ REPLY Cycle will retry before aborting	Ultimately Only One Route Re-Construction Cycle Is Valid

Table 2 : Summary of ABR RRCs under Different MH Migrations.

3.3 ABR Protocol Summary

Table 2 summarises the procedures of the routing protocol under different MH associativity states. The outstanding feature is that no RRCs are required so long as the property of associativity interlock remains valid. When this property is violated, the protocol will invoke a LQ or BQ process to quickly locate alternate routes.

Due to space constraint, details regarding the formats of the packet header, the routing and neighbouring tables along with the associated data flow acknowledgement and packet retransmission schemes will be mentioned in a pending journal paper.

4 Conclusion

In this paper, the problems associated with routing for ad-hoc mobile networks are presented. Because conventional distributed routing protocols incur extensive bandwidth, power and computation overheads for MHs in an ad-hoc mobile network, a bandwidth-efficient distributed routing protocol based on a novel concept of associativity is proposed.

The associativity concept exploits the spatial and temporal relationships of ad-hoc MHs to construct shorter and long-lived routes, resulting in fewer route re-constructions and hence higher attainable throughput. To fairly distribute the route relaying functions to support ad-hoc mobile communications, the route relaying load is identified as a new routing metric, so is the longevity of a route. The protocol is particularly suitable for conference size ad-hoc mobile networks.

Simulation results obtained from a migration-based ad-hoc mobile network simulator developed by the author confirm that the ABR protocol supports fast route recovery and produces shorter resultant paths. Further details will be found in a pending journal paper. Future work includes implementing the ABR protocol into existing WLANs so that ad-hoc mobile computing can be better supported.

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