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Distributed mobile tracking: a novel location management scheme for routing improvement in cellular IP networks

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Abstract

In this paper, a novel location management scheme, distributed mobile tracking (DMT), is proposed for routing improvement in Cellular IP networks. A mobile-tracking tree (MT-Tree) for each active mobile host is established by tracking the movement of the host in DMT. Two mechanisms, pruning process and growing process, are also proposed to improve DMT. Packet transmissions can follow the route on the MT-Tree instead of using the gateway route. Simulation results have shown that DMT has the advantages of shorter routing paths as well as load balance for wired links over the original gateway-based location management scheme. Moreover, three multicast protocols for Cellular IP are proposed: GBMP, GBMP-RO, and MTMP. In GBMP, the gateway is responsible for group management as well as multicast transmission. Multicast packets received by the base station are first forwarded to the gateway. The gateway then forwards the packets to each member of the group by multiple unicasting. GBMP-RO, a modified version of GBMP, adopts the idea of source routing for multicast transmissions. MTMP is mainly based on the MT-Tree routing scheme. However, if not all group members can be covered by MT-Tree routing, MTMP will instead adopt GBMP-RO for multicast transmission. Simulation results demonstrate that MTMP has the advantages over GBMP and GBMP-RO in terms of load balance in the Cellular IP network.

Keywords: Location management; Cellular IP; Routing; Multicast

1. Introduction

With the advent of personal communications technologies and the increasing demand of IP services for mobile users, mobility management [1–8] for IP-based data services has obtained intensive researches in recent years. Mobility management is an essential component in enabling mobility of hosts while maintaining the packet routing efficiency between the hosts. Different views for mobility resulted in different design philosophies and mechanisms in dealing with the mobile behavior. In the beginning of the research on the need for mobility, Mobile IP [9–14] was

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proposed to support global Internet mobility through the introduction of location directories and address translation agents. It is widely accepted that Mobile IP is inadequate for high mobility users in which frequent handoff is the common case, and instead, Cellular IP [15–18] was proposed.

Cellular IP provides local mobility and handoff support for frequently moving hosts, which means mobile hosts can migrate inside a Cellular IP network with little disturbance to active data flows. Integration of Mobile IP and Cellular IP has been addressed in [19,20]. The basic idea of the integration is using the two protocols at the same time but in different levels. Mobile IP is used for intersubnet mobility protocol (macro-mobility), while Cellular IP is employed for the intrasubnet mobility (micro-mobility). That is, Cellular IP provides local mobility support, but for mobility between different Cellular IP networks, it works with Mobile IP.

A Cellular IP network consists of a gateway, base stations and mobile hosts. The gateway connects the Cellular IP network to Internet. Cellular IP base stations are nodes that have an interface to a wireless network and interfaces to the wired network. Packets transmitted from mobile hosts are always routed from the base station to the gateway by a hop-by-hop shortest path routing.

As shown in Fig. 1, there are two kinds of traffic in a Cellular IP Network, *external traffic* and *internal traffic*. External traffic represents the class of traffic that is from or destined to an external host, while internal traffic is the traffic transmitted by a mobile host in the Cellular IP network and destined to another mobile host in the same Cellular IP network. The original handoff and routing mechanisms of the Cellular IP network require all the data packets, either external or internal, to be routed to the gateway before being routed to the destination. It results in a bad consequence that even the destination of the internal traffic is connecting to the same base station as the sender or the neighboring base station, the internal traffic is still routed to the gateway first. It implies that the gateway is inevitably becoming a hot spot of traffic and therefore results in the unbalanced traffic load of wired links in the Cellular IP Network. In this

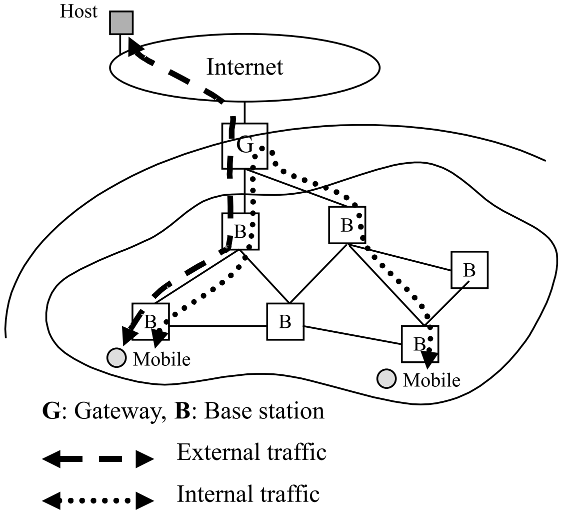

Fig. 1. Cellular IP access network.

paper, a new mobility management scheme called *Distributed Mobile Tracking* (*DMT*) is proposed to achieve high routing efficiency and to reduce the load of the gateway.

In DMT, the trace of an active mobile host is recorded and transformed to a routing tree (namely *MT-Tree*) by base stations. Base stations maintain the MT-Tree of a mobile host in the distributed manner, and each branch in the MT-Tree leads to the current position of the mobile host. Therefore, transmissions of IP packets destined to a mobile host can follow the route (branch) provided by the host's MT-Tree instead of adopting the original gateway-based routing scheme.

Moreover, two types of multicast routing protocols in Cellular IP are also proposed. The first one, which is called *Gateway-based Multicast Protocol* (*GBMP*), is the extension of the original gateway-based unicast routing scheme of Cellular IP. The basic version of GBMP adopts multiple unicast transmissions to achieve multicasting, while a modified version namely *GBMP with Route Option* (*GBMP-RO*) adopts the similar idea of the source routing scheme and greatly reduces the transmission cost. The other one is called *Mobile Tracking-based Multicast Protocol* (*MTMP*), which is based on the *MT-Tree routing* scheme.

Simulation study has been conducted to investigate the performance of the MT-Tree routing scheme as well as the performance of the multicast protocols. The results demonstrate that (1) MT-Tree routing is better than the original gateway routing in terms of routing efficiency and load balance of the wired links in the network, and (2) MTMP has a better performance than GBMP and GBMP-RO.

The rest of the paper is organized as follows. Basic idea of DMT and maintenance of the MT-Tree are explained in Section 2. Two mechanisms to improve DMT (MT-Tree) are proposed and presented in Section 3. DMT-based unicast routing protocol and multicast routing protocols, GBMP, GBMP-RO, and MTMP are presented in Section 4. Performance evaluation of DMT as well as the multicast protocols are presented in Section 5. Finally, Section 6 concludes this paper.

2. Distributed mobile tracking

2.1. Basic idea of DMT

Location management of mobile hosts plays an important part in managing mobility. The task of location management is to detect and register a mobile host's change of location and to deliver data packets along the best route. A centralized scheme of location management is adopted in Cellular IP to provide seamless mobility. The Cellular IP gateway maintains location information and a routing cache for each active mobile host in the network. Each base station also has a routing cache that maps a mobile host's IP address to the interface leading to the mobile host. All packets transmitted by mobile hosts regardless of their destination address are routed to the gateway first. The gateway then forwards each packet to its destination by the chain of mapping in the routing caches. Therefore, the routing path for internal traffic in a Cellular IP network is from the source mobile host to the gateway and then from the gateway to the destination mobile host.

From load balancing and routing efficiency viewpoint, the original routing scheme in Cellular IP as mentioned above is improper for internal traffic, since the locality relationship of source and destination has not been considered in the scheme. The ideal case is the shortest path from the source base station (mobile host) to the destination base station (mobile host) can always be found as in traditional Internet routing protocols like OSPF. However, in this case, all base stations must function as routers and exchange real-time location information for all mobile hosts in the network to maintain the routing table. This ideal, distributed routing scheme is actually impossible to provide seamless mobility and is infeasible for high mobility hosts, since the change of location for a mobile host may be faster than the update of the location/routing information.

Given that totally distributed routing scheme does not work for Cellular IP networks, we tried to build a partial routing tree by tracking the movement of the mobile host. Base stations that the host has visited record the trace of the mobile host and maintain the partial routing tree for the host. The partial routing tree for a mobile host is called *Mobile-Tracking Tree* (*MT-Tree*) in the paper. When a base station (B_s is relaying a packet to a mobile host (MH_x) that is not within its radio range, the base station has to decide the next base station the packet should be forwarded to. If (B_s is on MH_x's MT-Tree (which means MH_x visited B_s before), the packet can be routed to MH_x along MH_x's MT-Tree instead of being routed to the gateway. Thus, the locality relationship of source and destination is considered in the MT-Tree routing scheme, and the closer the destination host to the source host, the better performance the scheme will achieve. However, if the base station is not on the destination host's MT-Tree, the packet is forwarded to the destination according to the original scheme of Cellular IP. Therefore, the proposed routing scheme is a hybrid of MT-Tree routing and original gateway routing.

2.2. Maintaining the MT-Tree

In order to support MT-Tree routing, a new routing cache namely *MT-Cache* is added in base stations. The MT-Cache is used to record the movement of a mobile host. There are two possible values for a host's MT-Cache in a base station:

Null or *Identification* of a base station. The null value of the MT-Cache for a mobile host in a base station implies the host is currently within the range of the base station. On the other hand, if the value of the MT-Cache for a mobile host in base station B_x is the identification of another base station, e.g. B_y, it implies that the mobile host used to be within the range of B_x, but had moved to the range of B_y. For example, mobile host MH_x started from base station B_1 and orderly moved to the range of base stations B_2, B_3, and B_4. The mobile host is currently within the range of B_4. The value of the MT-Cache for MH_x in each base station is shown in Fig. 2. The illustration of the MT-Tree for MH_x is also displayed in the figure, which is the chain of MH_x's MT-Caches.

The MT-Cache for a mobile host is updated during the handoff process. A handoff occurs, when a moving mobile host leaves the range of a base station and approaches a new base station. During the handoff period, the mobile host sends a *MT-Cache-Update* packet to the old base station. The MT-Cache-Update packet carries the address of the mobile host and the identification of the new base station. The old base station that receives the MT-Cache-Update packet updates the MT-Cache of the mobile host with the identification of the new base station carried in the packet. The mobile host also sends another MT-Cache-Update packet (*Host Address, Null*) to the new base station to indicate that the host is now within the range of the base station. If there is no MT-Cache for the coming mobile host in the new base station, a new MT-Cache for the mobile host is created with the null value. If there is a MT-Cache existed in the new base station, the value of the MT-Cache for the mobile host is set to *Null*.

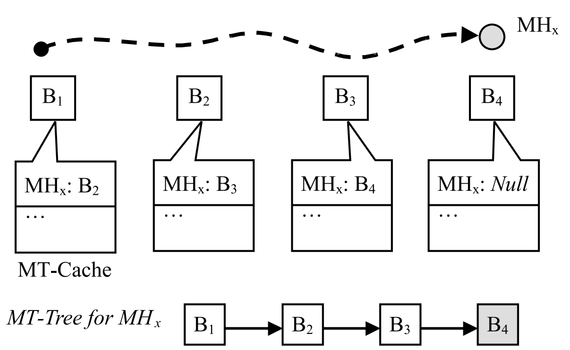

Fig. 2. An example of using MT-Cache.

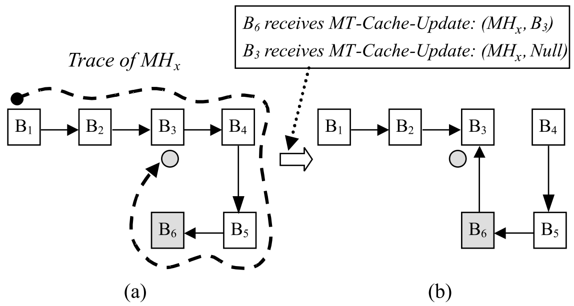

Fig. 3. An example of MT-Cache update: (a) old MT-Tree for MH_x and (b) new MT-Tree for MH_x.

We illustrate the process with the example in Fig. 3. The old MT-Tree for mobile host MH_x before handoff to new base station B_3 is shown in Fig. 3(a). When the handoff occurs, MH_x sends a MT-Cache-Update packet (MH_x, B_3) to the old base station B_6 indicating that the new base station for MH_x is B_3, and sends a MT-Cache-Update packet (MH_x, *Null*) to the new base station B_3 indicating MH_x is within the range of B_3. After the update of the MT-Caches in B_3 and B_6, the new MT-Tree for MH_x is shown in Fig. 3(b).

It is worth mentioning that the new MT-Tree after the update of the MT-Cache for handoff is still a tree (i.e. no loops in the MT-Tree) as explained in the following. A loop occurs in the trace of a mobile host when the mobile host revisits a base station it visited before, e.g. B_3–B_4–B_5–B_6–B_3 in Fig. 3(b). Since the MT-Cache of the mobile host in the current base station is set as *Null* to indicate the current position of the host, the link between B_3 and B_4 breaks and no loop exists in the new MT-Tree. Therefore, the MT-Tree for a mobile host is actually a set of branches that all lead to the current position (base station) of the host.

2.3. Discussion

In order to support distributed mobile tracking, we have assumed in Section 2.1 that a mobile node must be able to inform the old base station the ID of the new base station before handoff to the new base station. However, this assumption may be a little too strong since for some handover mechanisms a mobile node may not know the ID of the new base station until the handover process is almost finished, and the mobile node has no way to inform the old base station about its new location via the wireless interface. In such case, the mobile node instead informs the new base station the ID of the old base station, and the new base station is responsible for the update of MT-Cache in the old base station on behalf of the mobile node.

The idea of DMT can be also applied to more hierarchical network architectures like UMTS, in which three base stations are interconnected through a Radio Network Controller (RNC) and RNCs are interconnected by wired links. In UMTS, RNC is responsible for routing in the wired network, and thus MT-Cache for each mobile node should be maintained in RNCs, instead of in the base stations. Moreover, the location information in MT-Cache for a mobile node in UMTS is composed of (1) the ID of a RNC and (2) the ID of a base station under that RNC. An intraRNC handover only requires update of the ID of the base station in MT-Cache, and only the same RNC is involved. An interRNC handover is more complicated. MT-Cache in the new RNC as well as the MT-Cache in the former RNC must be updated.

3. Improvement of DMT

The MT-Tree of a mobile host represents the set of routes (paths) leading to the mobile host. However, since the MT-Tree is based on the trace of the mobile host, there are cases that the routing path along the MT-Tree is longer than that of the original scheme through the gateway. Thus a *pruning process* is proposed to prune long branches of the MT-Tree such that shorter routes are always provided by the MT-Tree routing. On the other hand, given that the MT-Tree of a mobile host is a partial routing tree as mentioned in Section 2.1, the coverage of the MT-Tree affects the hit ratio of MT-Tree routing as well as the performance of DMT. Hence, a *growing process* of MT-Tree is proposed to increase the coverage of the MT-Tree for each mobile host.

3.1. Pruning of the MT-Tree

The pruning process for a mobile host's MT-Tree is to guarantee the path along the tree is never longer than the path of original gateway routing. A base stations (B_x) activates the pruning process when a packet received from the wireless interface (mobile host) is routed along the destination's MT-Tree (MH_x's MT-Tree). The pruning process compares the hop count of the path along MH_x's MT-Tree with the hop count of the gateway routing. If the path along the MT-Tree is longer, base station B_x is removed from MH_x's MT-Tree, which means MH_x's MT-Cache is cleared in base station B_x. Moreover, in order not to have an isolated branch of the MT-Tree left in the network, B_x needs to inform its preceding nodes that belong to the same being cut branch to clear MH_x's MT-Cache.

A new control packet namely *MT-Tree-Probe* packet is used for the pruning process, and we illustrate the process with an example. As shown in Fig. 4(a), base station B_1 activates the pruning process for MH_x's MT-Tree and transmits a MT-Tree-Probe packet along the tree. The hop count from B_1 to the gateway G ($HC_{B_1-G} = 1$) is carried in the packet. The MT-Tree-Probe packet also records the hop count of the MT-Tree route (HopCount = 5). When the MT-Tree-Probe packet arrives in the destination base station B_7, the hop count of the gateway routing is computed as the summation of HC_{B_1-G} and HC_{B_7-G}, in which HC_{B_1-G} is carried in the packet and HC_{B_7-G} could be easily obtained by B_7. Since the hop count of the MT-Tree routing is longer than that of the gateway routing, base station B_1 should be removed from MH_x's MT-Tree. Therefore, B_7 notifies B_1 to clear MH_x's MT-Cache, and B_1 notifies its preceding node B_0 to clear MH_x's MT-Cache. The result of the pruning process for the example is shown in Fig. 4(b).

Although it was mentioned that the pruning process is activated when the base station receives a packet from a mobile host and the packet is routed along the MT-Tree, the base station may activate the pruning process for the same MT-Tree at regular intervals to reduce the system load as well as the network traffic of control packets.

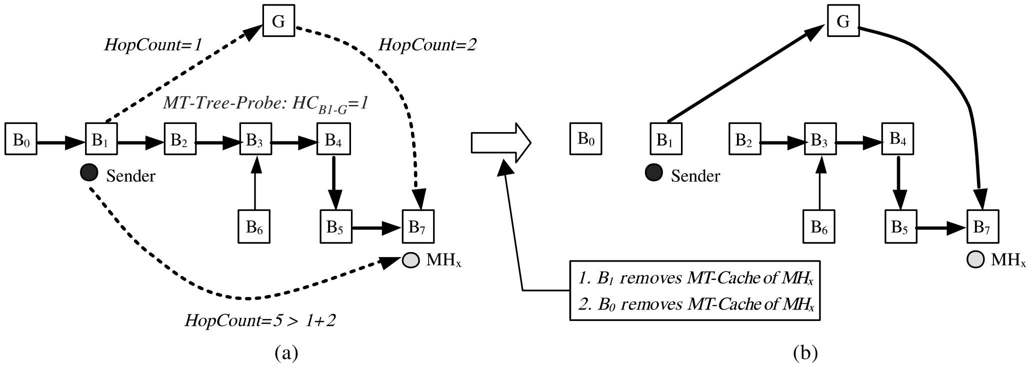

Fig. 4. An example of the pruning process: (a) before the pruning process and (b) after the pruning process.

3.2. Growing of the MT-tree

The purpose of the growing process is to extend the coverage of the MT-Tree such that non-visited base stations for a mobile host can be included in the MT-Tree of the host. A base station transmits its MT-Cache information (MT-Cache table) to its neighboring base stations in the growing process. On receiving the MT-Cache table, neighboring base stations update their MT-Cache tables as follows. We assume that base station B_r has received MT-Cache information from its neighbor B_s. MT-Cache Entries that do not exist in base station B_r are added in the MT-Cache table in base station B_r, while MT-Cache entries that are already found in B_r remained unchanged. In this way, the coverage of some MT-Trees is extended by one more hop. Moreover, given that no isolated branch for a mobile host exists in the network, tree structure (no loops) of the MT-Tree for a mobile host is still maintained after the growing process. An example of the growing process is shown in Fig. 5, in which only one MT-Tree (for MH_x) is depicted in the figure.

In order to maintain the large coverage for the MT-Tree as time goes by, base stations should perform the growing process in a periodic manner, i.e. neighboring base stations should exchange their MT-Cache tables periodically just like what the routers in *Routing Information Protocol* (*RIP*) do. However, periodic exchange of the MT-Cache table introduces large overhead for base stations. Hence, base stations performing the growing process should only transmit updates of MT-Cache entries to their neighboring base stations to reduce the overhead.

4. Routing protocols

4.1. Unicast transmission

As mentioned in Section 2.1, there are cases that the source base station is not on the MT-Tree of the destination mobile host (that is, the base station does not contain the corresponding MT-Cache entry for the destination mobile host), so MT-tree routing does not get rid of the original gateway routing scheme. Thus, unicast transmission of packets is actually a hybrid of MT-Tree routing and gateway routing. The hybrid routing scheme is summed up as follows. When a base station has received a packet from the wireless interface and there is a MT-Cache for the destination of the packet in the base station, the packet is routed along the MT-Tree; otherwise, the packet is routed to the gateway according to the original routing scheme. Since the MT-Tree routing coexists with the original gateway routing, the operations for handoff in the original scheme are still necessary, which means two types of handoff in Cellular IP, *hard handoff* and *semisoft handoff* [15,17] are still provided, and the route-update packet is transmitted after handoff from the new base station to the gateway for maintaining the new uplink of the mobile host to the gateway.

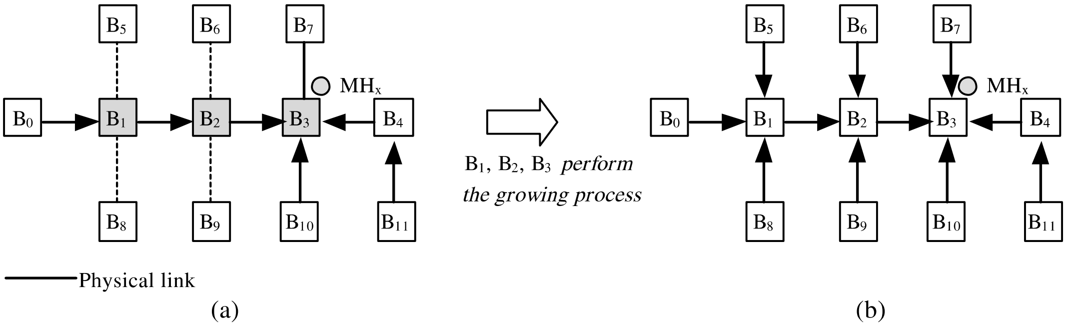

Fig. 5. An example of the growing process: (a) before the growing process and (b) after the growing process.

Moreover, mobile tracking is only engaged in active calls (active hosts) to maintain the feature of *passive connectivity* in Cellular IP. A timer should be associated with the MT-Cache, and data packets are used to maintain and refresh the cache. While the MT-Tree is used for routing packets, the mobile host transmits route-update packets on the uplink at regular intervals to maintain original gateway routing.

4.2. Multicast transmission

Three multicast protocols are proposed in this paper. Two of them are based on gateway routing, and the other one is based on MT-Tree routing. They are explained in the following respectively.

4.2.1. Gateway-based multicast protocol (GBMP)

Since the handoff and routing mechanisms of Cellular IP require all the data packets to be routed to the gateway before being routed to the destination, the most straightforward way to extend Cellular IP for multicast support is to equip the gateway with the ability of group management and be responsible for multicast transmission. Thus the gateway in GBMP is responsible for establishing the information of group membership, and all multicast packets transmitted from mobile hosts are first forwarded to the gateway according to the original routing scheme of Cellular IP. Since the gateway maintains the member list for each multicast group, the gateway forwards the multicast packet to the group members. The original routing scheme and the handoff mechanism in Cellular IP remain unchanged in GBMP.

The gateway maintains a *Group Membership Table* to keep track of the membership information for each multicast group in the Cellular IP network. The table includes entries of group identification (class-D IP address) and the identifications of the members that belong to the group. Joining or leaving a multicast group requires the mobile host sending the corresponding *Internet Group Management Protocol* (*IGMP*) message to the gateway. For joining a multicast group, the mobile host sends a *join* request to the base station. The base station receiving the join request forwards the request to the gateway on a hop-by-hop basis as it does for the case of regular IP packets. On receiving the join request, the gateway adds the IP address of the mobile host to the member list of the group indicated in the request. For leaving a multicast group, the mobile host sends a *leave* request to the base station and the gateway removes the IP address of the mobile host from the member list of the group.

Multicast transmission in GBMP is composed of two stages as shown in Fig. 6. First, on receiving a multicast packet (with a class-D destination address) from the radio link, the base station forwards the packet to the gateway as it does for regular data packets. Second, the gateway looks up the group members for the destination address of the multicast packet in the group membership table, and forwards the packet to each of the group members by multiple unicasting. More specifically, the gateway uses unicast tunneling (IP-in-IP encapsulation) to forward the packet to each of the group members. The source address of the outer IP header is the address of the gateway,

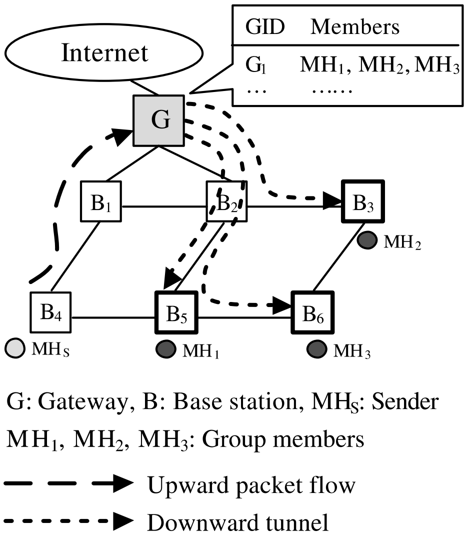

Fig. 6. Gateway-based multicast protocol.

and the destination address of the outer IP header is the address of the mobile host that is one of the group members. Routing of the IP-in-IP packet is according to the original routing scheme in Cellular IP. The destination base station, which is the end of the tunnel, needs to de-encapsulate the outer IP header of the IP-in-IP packet and transmit the multicast packet to the destination mobile host via the wireless interface. It is worth mentioning that in GBMP and other multicast protocols proposed in the paper the sender does not need to be a member of a group for sending packets to the group.

4.2.2. Gateway-based multicast protocol with route option (GBMP-RO)

In order to reduce the cost of multicast transmission in GBMP, an IP option namely *GBRouteOption* is defined. Instead of using multiple unicasting, the GBRouteOption field in a multicast packet is used to carry addresses of the group members to which the packet should be forwarded. Using GBRouteOption for GBMP is similar to the scheme of multicast source routing, and the new protocol is called *GBMP with Route Option* (*GBMP-RO*) in the paper. When a multicast packet has been received for forwarding, the gateway gets all the members' addresses of the destination group from the group membership table. The routing cache maintained in the gateway for unicast transmission is then used to determine the next hop for each destination member. For the members with the same next hop of routing, the gateway transmits a single multicast packet with GBRouteOption recording these members' addresses.

Base stations must be able to recognize and interpret the GBRouteOption field in multicast packets to support GBMP-RO. On receiving a multicast packet, the base station examines the GBRouteOption field to determine all the destination mobile hosts of the packet and transmits the multicast packet with updated GBRouteOption to proper next hops according to its routing cache.

4.2.3. Mobile Tracking-based Multicast Protocol (MTMP)

Group management in MTMP is the same as GBMP, but multicast transmission in MTMP mainly follows the MT-Tree routing scheme as explained in the following. On receiving a multicast packet from the radio link, the base station first makes an IGMP *query* request to the gateway for retrieving the member list of the destination group. Since the base stations in the Cellular IP network do not maintain the membership information for each group, the multicast packet needs to carry the addresses of the group members for forwarding. For that reason, an IP option namely *MTRouteOption* for MTMP is defined. The MTRouteOption field is used to carry the addresses of the mobile hosts that the packet should be forwarded to by MT-Tree routing.

By examining the MT-Cache table, the base station decides the next hop for each group member. For members with the same next hop, the base station generates a multicast packet with these members' addresses in the MTRouteOption field and transmits the packet to the next hop. Fig. 7 shows an example of using MTRouteOption. Base station B_1 has received a multicast packet destined to group G_1 whose members are MH_1, MH_2, and MH_3. Since MT-Cache indicates that the next hop for group members MH_1 and MH_3 is base station B_2, B_1 generates a multicast packet

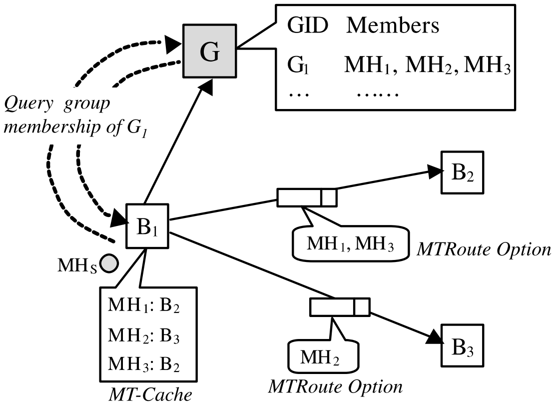

Fig. 7. E.g. using *MTRouteOption*.

with *MTRouteOption* (MH_1, MH_3) and forwards the packet to base station B_2. Similarly, a multicast packet with *MTRouteOption* (MH_2) is generated and forwarded to base station B_3. When receiving a multicast packet with MTRouteOption, the base station checks the destination members of the packet in the MTRouteOption field, looks up the next hop for each member in MT-Cache, and transmits multicast packets with updated MTRouteOption on proper outgoing links. The destination base station broadcasts the multicast packet to the group member(s) via the radio link.

There are cases that the source base station does not have the corresponding MT-Cache entry for a destination mobile host, which means that the base station is not on the MT-Tree of the destination host. In order not to increase the transmission cost, MTMP adopts an all-or-none policy for multicasting. That is, MT-Tree routing is used only when all destination mobile hosts can be reached by MT-Tree routing. Otherwise GBMP-RO is used instead for multicast transmission. Thus, MTMP is actually a hybrid scheme of multicast MT-Tree routing and GBMP-RO.

In order to reduce the overhead of retrieving the member list from the gateway, the base station does not need to issue an IGMP query request each time it receives a multicast packet from the radio link. Instead, the base station establishes a signaling channel from the gateway for updating the membership information of the multicast group. The gateway notifies the base station of the change of membership whenever a mobile host joins/leaves the group. The base station explicitly closes the signaling channel whenever there is no need to maintain the channel such as the sender of the multicast group has moved out from the base station.

4.3. Discussion

The overhead of unicast transmission introduced by DMT includes: (1) for mobile hosts, the need of transmitting MT-Cache-Update packets to the old base station as well as the new base station during handoff, (2) for base stations, the need of maintaining the MT-Cache and the operations of the pruning process as well as the growing process. On the other hand, for multicast transmission, all of GBMP, GBMP-RO, and MTMP require the gateway in charge of group management. Base stations supporting GBMP need to be able to handle tunneling (IP-in-IP) operations for multicasting by multiple unicasting. GBMP-RO and MTMP require base stations to recognize two types of route option, *GBRouteOption* and *MTRouteOption* to support multicasting.

5. Performance evaluation

5.1. Simulation environment and performance criteria

The network topology for the Cellular IP network in the simulation is an 8×8 mesh. Each node in the mesh represents a base station and the gateway is located at the corner of the mesh. There are 5,000 mobile hosts in the network. Initial locations for the hosts are randomly selected from the base stations. In order to model the mobility of the hosts, time is slotted and a parameter called *MoveProb* (*Movement Probability*) is used in the simulation. *MoveProb* represents the probability that a mobile host leaves its current base station in the next time slot. Thus, we could model high mobility of hosts by assigning a large value of *MoveProb*. When a mobile host decides to leave the current base station in the next time slot, its next base station is randomly selected from the neighboring base stations.

In each time slot, 2000 sets of the sender and the group members (receivers) are randomly selected to evaluate the performance of the multicast routing schemes. Total run time in the simulation for each scheme (protocol) is 600 time slots. There are three performance criteria for comparing the schemes: (1) the *average hop count* from the sender to the group members, (2) the *average cost of multicasting*, and (3) the *load* of each wired link in the Cellular IP network. The cost of multicasting is defined as the total number of data packets generated in the Cellular IP network for a single multicast transmission. The load of each wired link is calculated as follows. Total number of connections in each wired link is recorded during the simulation. When the 600th time slot is up, the load of a wired link is computed as the number of connections in the link divided by the maximum number of connections among all wired links. That is, the load of the link with the maximum number of connections is set to 1, and the load of other links is calculated by normalizing the number of connections to the maximum number of connections.

5.2. Performance of unicasting

Fig. 8 shows the average hop counts of the proposed hybrid (DMT) scheme and the gateway routing scheme with $MoveProb = 0.2$, 0.5, and 0.8. The effect of the growing process is also shown in the figure. Moreover, the average hop count of the ideal routing scheme (shortest path routing) is calculated and shown for reference in the figure. As shown in the figure, the proposed routing scheme regardless the value of *MoveProb* can always find better routes than the gateway routing, which is the effect of the pruning process. With $MoveProb = 0.8$ and tree growing process enabled, the average hop count for the proposed routing scheme is about 9 at the 600th) time slot, which is only 64% of the average hop count ($= 14$) for the gateway routing. It means 36% routing improvement could be achieved by the proposed DMT scheme.

A large value of *MoveProb* implies high mobility of mobile hosts, so the MT-Trees for a large *MoveProb* may have a large coverage. A large coverage implies a higher hit ratio of selecting the MT-Tree routing for packets, thus a better route can be obtained earlier. The growing process of MT-Tree also helps the MT-Tree routing scheme get the better route earlier as shown in Fig. 8. The hit ratios of the MT-Tree routing with different values of *MoveProb* are displayed in Fig. 9. The hit ratio of the MT-Tree routing with $MoveProb = 0.8$ at the 600th time slot is about 0.8. The average length of the route on the MT-Tree at the 600th time slot can be calculated as $(9 - 0.2 * 14)/0.8 = 7.75$ (the average hop count for the proposed scheme $= 9$, the average hop count for the gateway routing $= 14$).

Fig. 10 displays the load of each wired link in the network for the gateway-based routing and MT-Tree routing respectively. The assignment rule for the index of each link is that a closer link to the

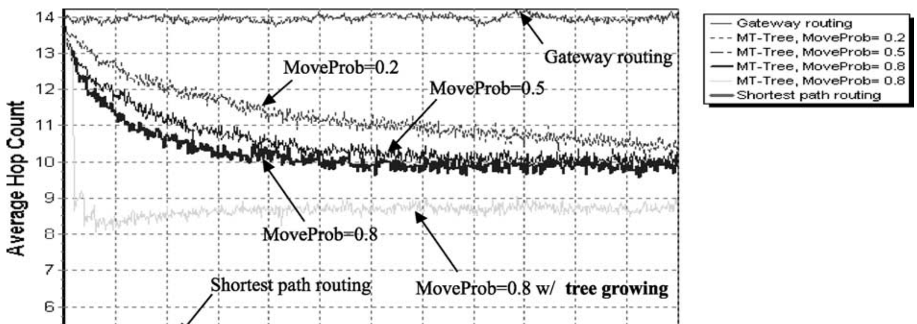

Fig. 8. Average hop counts (unicast).

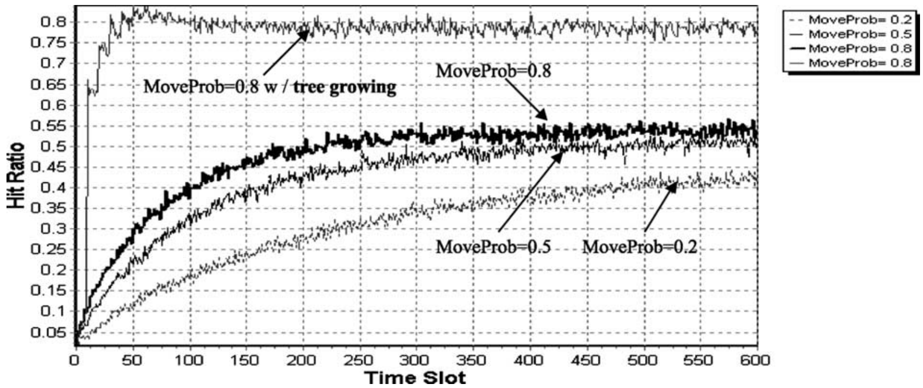

Fig. 9. Hit ratios for MT-Tree (unicast).

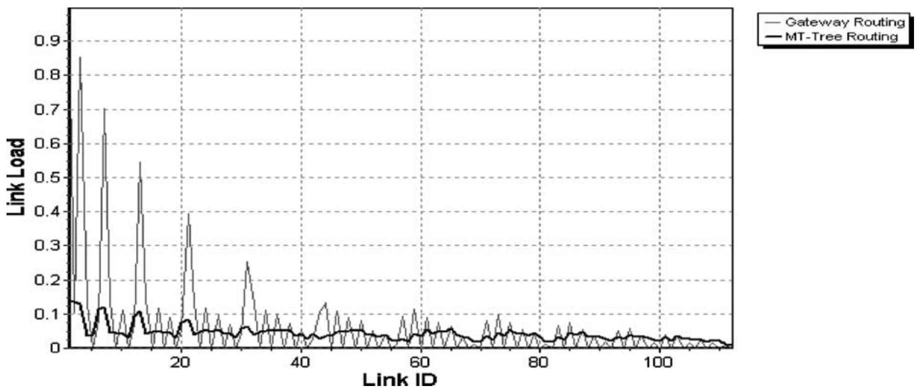

Fig. 10. Link load at the 600th time slot ($MoveProb = 0.8$, tree growing, unicast).

gateway gets a smaller index. Load unbalance for the gateway routing can be found since closer links to the gateway get much more load than other links. On the other hand, the figure also demonstrates the improvement of the MT-Tree routing in load balancing.

5.3. Performance of multicast protocols

The average hop count of GBMP-RO is the same as GBMP (about 14), and MTMP always obtains a smaller average hop count (under 9) than the other two. Average costs of multicasting for the protocols are displayed in Fig. 11. It shows that the cost of multicast transmission of GBMP is the highest among the three protocols and the cost of MTMP is slightly higher than that of GBMP-RO when the group size is getting large. The reason for the higher cost of MTMP is explained in the following.

Since the MT-Tree for each mobile host is constructed independently by tracking the movement of the host, there is no much correlation among the MT-Trees of the members in a group. As the group size is getting large, there will not be many share links for multicast transmission along the MT-Trees of the group members. On the other hand, GBMP-RO is much like the core-based tree (CBT) multicast routing protocol and more share links for multicast transmission can be obtained. However, since the average hop count for MTMP is always smaller than that of GBMP-RO, the increase of the cost of transmission in MTMP is not too much.

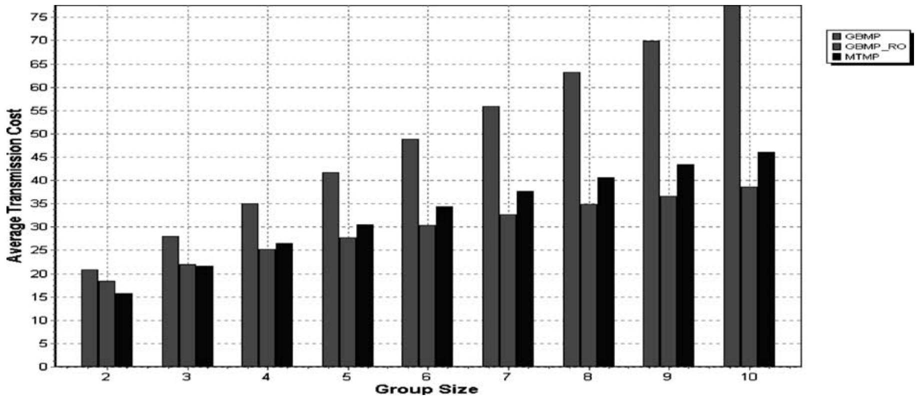

Fig. 11. Average transmission cost (multicast).

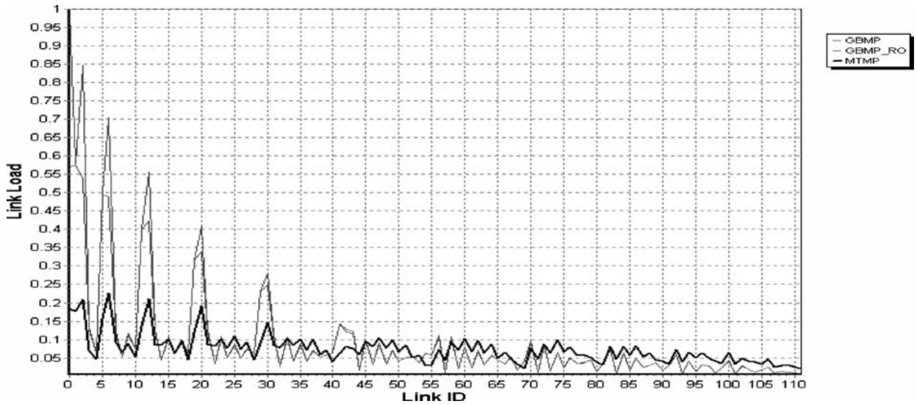

Fig. 12. Link load at the 600th time slot (group size = 2).

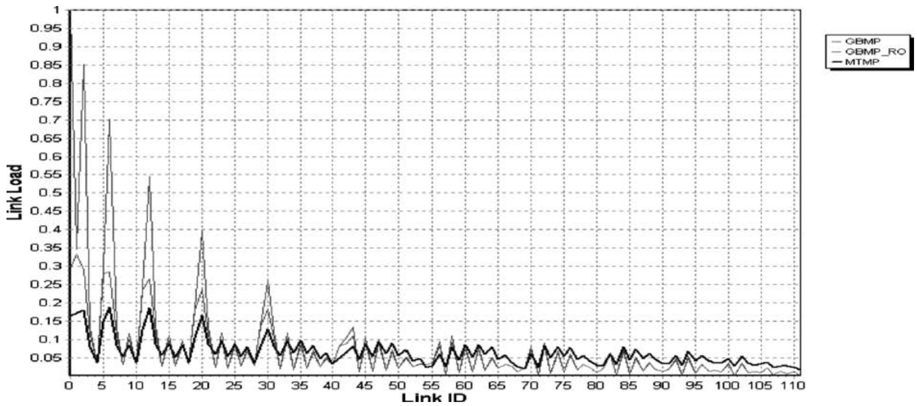

Fig. 13. Link load at the 600th time slot (group size = 4).

Figs. 12–14 display the load of each wired link in the network for different multicast routing schemes with group sizes 2, 4, and 8 respectively. These figures show the effect of load balancing by

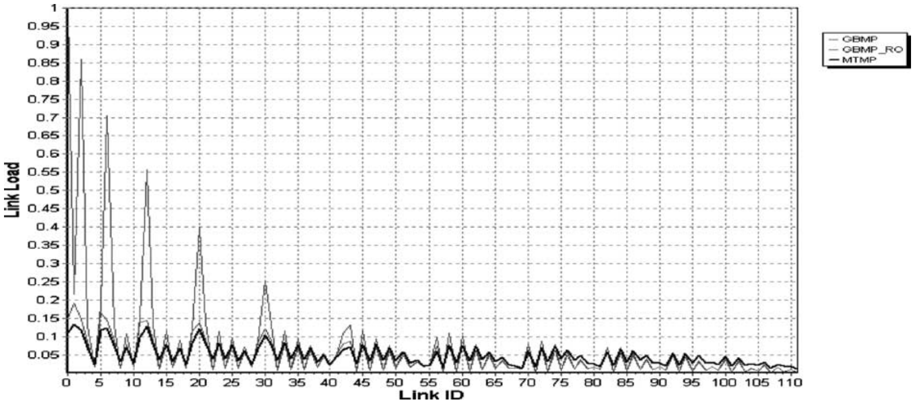

Fig. 14. Link load at the 600th time slot (group size = 8).

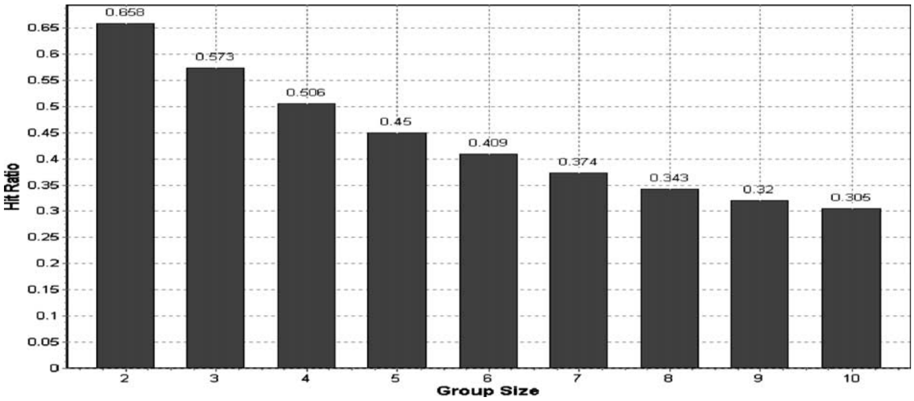

Fig. 15. Hit ratios of MT-Tree routing in MTMP.

MTMP. Either GBMP or GBMP-RO has inevitably made the gateway a hot spot of traffic. In order to investigate more about the behavior of MTMP, the hit ratio of MT-Tree routing in MTMP is calculated and shown in Fig. 15. It shows that a larger group size results in a smaller hit ratio of MT-Tree routing. Therefore, as the group size is getting large, MTMP is more like GBMP-RO.

6. Conclusion

In this paper, a novel location management scheme, DMT, is proposed for routing improvement in Cellular IP networks. DMT builds a MT-Tree for each active mobile host in the Cellular IP network in a distributed manner. Two processes, the pruning process and the growing process, are proposed to improve the performance of DMT. The pruning process is used to prune the long branches on the MT-Tree such that better (shorter) routes can always be found along the tree than the gateway routing. The growing process, on the other hand, is used to increase the coverage of MT-Trees. Packet transmissions can follow the route on the MT-Tree instead of using the gateway route. More specifically, the source base station routes the packet to the destination along the MT-Tree if the base station is on the destination host's MT-Tree, otherwise the base station routes the packet by the original routing scheme. The overhead introduced by DMT includes: (1) for mobile hosts, the need of transmitting *MT-Cache-Update* packets to the old base station as well as the new base station during handoff, (2) for base stations, the need of maintaining the *MT-Cache* and the operations of the pruning process as well as the growing process.

For multicast transmissions in Cellular IP networks, three multicast protocols are proposed in the paper: *GBMP*, *GBMP-RO*, and *MTMP*. In GBMP, the gateway is responsible for group management as well as multicast transmission. Multicast packets received by the base station are first forwarded to the gateway. The gateway then forwards the packets to each member of the group by multiple unicasting. GBMP-RO, a modified version of GBMP, adopts the idea of source routing for multicast transmissions. Group management in MTMP is the same as GBMP and GBMP-RO, but multicast transmission in MTMP is mainly based on the MT-Tree routing scheme. However, if not all group members can be covered by MT-Tree routing, MTMP will instead adopt GBMP-RO for multicast transmission.

Simulation results have shown that DMT has the advantages of over the original gateway-based location management scheme in terms of shorter routing paths as well as link load balance. Similarly, MTMP has the same advantages over GBMP and GBMP-RO. However, as the group size is getting large, MTMP is more like GBMP-RO.

In summary, the contributions of this paper are listed in the following:

1. A new location management scheme namely DMT is proposed for Cellular IP networks.
2. Two mechanisms, the pruning process and the growing process, for improving DMT are suggested.
3. Three multicast protocols for Cellular IP are proposed. Two of them (GBMP and GBMP-RO) are gateway-based. The other one (MTMP) is DMT-based.
4. Simulation results demonstrate that DMT-based protocols, either for unicasting or multicasting, have the advantage of better performance over their gateway-based counterparts.

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