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A Novel Location Management Scheme and Routing Protocol for Group Communications in Cellular IP Networks*

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SUMMARY In this paper, a novel location management scheme called Distributed Group Tracking (DGT) for group communications in Cellular IP networks is proposed. In DGT, Base stations track each member of a group and build a share multicast routing tree called DGT-Tree for the group in a distributed manner. Transmission of multicast packets among group members is along the group's DGT-Tree. Simulation study has demonstrated that a better performance can be achieved by DGT over the gateway-based counterpart in terms of transmission cost as well as link load balance. Moreover, the average number of DGT operations decreases as the group size increases, showing the good scalability of the DGT scheme, and the average number of control packets as well as the cache requirement for performing DGT operations demonstrate the moderate overhead introduced by DGT.

key words: *cellular IP, mobility management, multicast, group communications*

1. Introduction

Mobility management at IP layer [1]–[6] is an essential component in wireless mobile networking. *Mobile IP* [7]–[11] was proposed to support global Internet mobility through the introduction of location directories and address translation agents. However, these mechanisms for supporting mobility make Mobile IP inadequate for high mobility users in which frequent handoff is the common case, and therefore *Cellular IP* [12]–[14] 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 [15]–[18]. The basic idea of the integration is using the two protocols at the same time but in different levels. Mobile IP is used for inter-subnet mobility protocol (*Macro-mobility*), while Cellular IP is employed for the intra subnet mobility (*Micro-mobility*). That is, Cellular IP provides local mobility support, but for mobility between different Cellular IP networks, it works with Mobile IP.

It was pointed out in our previous work [19] that the handoff and routing mechanisms in Cellular IP require all the data packets to be routed to the gateway before being routed to the destination. It results in a bad consequence that for internal traffic of which the packets are transmitted by a mobile host in the Cellular IP network and destined to another mobile host in the same Cellular IP network, the traffic is still routed to the gateway first, even the destination of the traffic is connecting to the same base station as the sender or a neighboring base station. It implies that the gateway is inevitably becoming a hot spot of traffic and therefore results in the phenomenon of load unbalance among wired links in the Cellular IP Network. To remedy the problem incurred by the original Cellular IP handoff and routing scheme, *Distributed Mobile Tracking* (*DMT*) was proposed in our previous work [19].

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 a distributed manner, and each branch in the MT-Tree leads to the current position of the mobile host. Therefore, transmission of IP packets destined to a mobile host can follow the route (tree branch) provided by the host's MT-Tree instead of using the original gateway-based routing scheme. There are cases that MT-Tree routing is not available since the trace of a mobile host (i.e. its MT-Tree) cannot cover all potential source base stations. In such cases, packets are forwarded to the destination according to the original scheme of Cellular IP. Simulation results had demonstrated a better performance of DMT than the original routing scheme in Cellular IP in terms of link load balancing and routing efficiency.

A multicast extension to DMT, which was called *Mobile Tracking-based Multicast Protocol* (*MTMP*), was also proposed in our previous work. MTMP uses MT-Tree routing as long as the source base station finds that MT-Tree routing is available for all receivers of the destined group. Otherwise, the multicast traffic is forwarded to the gateway, which is the manager of group membership information. The gateway is responsible for transmitting the packets to all receivers. The gateway-based multicasting was called *GBMP-RO* (*Gateway-based Multicast Protocol with Route Option*) in which an IP option was defined to carry addresses of the group members to which the multicast packet should be forwarded. Simulation studies had shown the effect of load balancing as well as the low transmission cost by MTMP. However, as the group size increases, the hit ratio of MT-Tree routing in MTMP decreases drastically that makes MTMP behave more like GBMP-RO.

The major reason that DMT does not perform so well in

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MTMP as in the unicast case is because DMT tracks each individual mobile host independently. Since the MT-Trees of all members in a same group are independently maintained, the chances of taking advantage of MT-Tree routing are slim for a large group. In order to cope with the problem of DMT in multicast transmission, a new scheme of mobile tracking, which is called *Distributed Group Tracking* (*DGT*), is proposed in this paper.

Unlike DMT, DGT builds and maintains a shared routing tree called *DGT-Tree* for all members in a group. The DGT-Tree of a group connects all members in the group such that a multicast packet originated from one of the members can be routed to all the other members along the group's DGT-Tree. It is worth mentioning that any mobile host is allowed to send multicast packets to any group in MTMP and GBMP-RO. However, in DGT, only group members are allowed to transmit multicast packets to the group. Therefore, DGT is specially designed for group communications in which only the members in a group are senders and receivers of the group. As will be explained in Sect. 2.2, DGT requires the original CIP routing scheme for transmission of signaling messages, and the gateway in CIP is responsible for group membership management, which means DGT is not totally distributed. However, DGT is distributed in the sense of multicast tree maintenance to deal with mobility of group members.

Applications of the DGT protocol may include: (1) teleconferencing in which part of or all of the participants are mobile users in the same wireless access network, (2) distributed games for mobile users, (3) live video multicasting, and (4) typical multicast applications such as news or stock quote multicasting.

To provide multicasting or group communications with mobility functions, several techniques have been proposed on the basis of Mobile IP, such as *MoM* (*Mobile Multicast*) [20], *MMA* (*Multicast by Multicast Agent*) [21], [22], and *MMROP* (*Mobile Multicast with Route Optimization*) [23], etc. Banerjee and Das [24] proposed an analysis for *Remote Subscription* (*RS*) based multicasting in cellular networks, considering user mobility which directly affects the multicast group size and indirectly affects the cost of multicast delivery tree. On the other hand, multicast-related research for Cellular IP or other Micro-mobility protocols has received less attention in the literature. Giovanardi, Mazzini, and Rossi [25] proposed a simple analytical model for multicast mobility support in cellular systems by means of multicast agents placed at each base station. The model is useful to compute two basic performance indexes: the handover latency and resource utilization time, but it is not concerning about the multicast routing issue as in DGT. A distributed algorithm for reliable multicast in mobile cellular networks was proposed by Prakash, Schiper, and Mohsin [26], in which the routing issue is not the major concern.

Sato, Katsumoto, and T. Miki addressed Cellular IP routing in their work [27] for multicast technique supporting source mobility. The proposed protocol was called *Source Mobility Support Multicast* (*SMM*). SMM is based on a concept where multicast tree is constructed over Cellular IP network, in which a *Source Point Tree* (*SPT*) [28] and a *Rendezvous Point Tree* (*RPT*) [29], [30] are combined into one multicast tree. Since SMM is dealing with inter-CIP data flows, the gateway in each CIP network is the *Rendezvous Point* of the multicast tree. As in our previous work of DMT, DGT is proposed to deal with the intra-CIP multicast data flows. And as will be presented in the following section, the gateway in DGT is only responsible for group membership management. Multicast routing among group members is accomplished by the distributed cached information for the group in each base station.

Simulation studies have been conducted to investigate the performance of DGT for group communications. Simulation results demonstrate that DGT outperforms MTMP and GBMP-RO in terms of transmission cost and load balancing. The results also show that DGT can effectively reduce the maximum path length in multicast transmission over GBMP-RO. Moreover, a larger group size results in fewer DGT-related operations, which demonstrates the good scalability of DGT in supporting group communications.

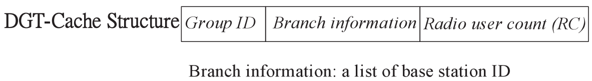
The rest of the paper is structured as follows. The basic idea of Distributed Group Tracking and the construction of the DGT-Tree for a group are explained in Sect. 2. Mechanisms for maintaining DGT-Tree and handling mobility of group members are presented in Sect. 3. Simulation environment and results for performance evaluation are presented in Sect. 4. Finally, Sect. 5 concludes this paper.

2. Distributed Group Tracking

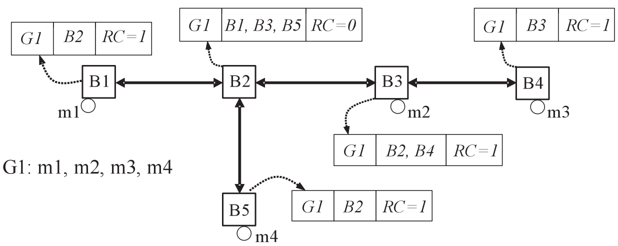
2.1 Basic Idea

The main idea of DGT is to build a shared multicast routing tree (*DGT-Tree*) among group members such that multicast packets transmitted by any of the members are routed to other members along the tree. Each link (branch) on a DGT-Tree is thus bi-directional. In order to make DGT work properly, some issues must be addressed: (1) the data structure in base stations for representing a DGT-Tree, (2) management of the dynamic membership of a group, and (3) mobility of group members. Management of group membership and the construction of the DGT-Tree for a group are presented in Sect. 2.2. Mechanisms for dealing with mobility of group members are proposed in Sect. 3. In the following, we present the data structure for maintaining DGT-Tree.

As in Distributed Mobile Tracking, a new cache called *DGT-Cache* is defined in DGT. DGT-Cache is used to represent the branches of a DGT-Tree. Base stations in the Cellular IP network track all members in a group concurrently and maintain DGT-Cache for the group's DGT-Tree in a distributed manner. The data structure of DGT-Cache is shown in Fig. 1(a), in which three fields are defined in each DGT-Cache entry: *Group ID*, *Branch information*, and *Radio User Count* (denoted by *RC*). Group ID records the identification (usually a class-D IP address) of the group. Branch information records the branches of the DGT-Tree



(a) Structure of DGT-Cache.



(b) Example of DGT-Tree.

Fig. 1 Using DGT-cache for representing DGT-tree.

that are connected to the base station keeping the DGT-Cache. Branch information is a list of base station ID. RC records the number of group members that are currently connected to the base station via radio interface. For instance, DGT-Cache entry ($G1$: B_y, B_z: RC=1) in base station B_x means that there are two branches on $G1$'s DGT-Tree that are connected to base station B_x: branch $B_x - B_y$ and branch $B_x - B_z$. RC=1 means there is currently one group member connecting to base station B_x via wireless interface. Note that we require the branches on a DGT-Tree to be bi-directional. Thus, there must be a DGT-Cache entry for $G1$ in base stations B_y and B_z containing information for branches $B_y - B_x$ and $B_z - B_x$. An example of using DGT-Cache to represent DGT-Tree is illustrated in Fig. 1(b).

DGT-Tree provides an easy way for multicast transmission among group members. For example, if mobile user $m4$ in Fig. 1(b) wants to transmit a multicast packet to other members in $G1$, it does that via its radio link to base station $B5$. On receiving the multicast packet destined to group $G1$, base station $B5$ realizes from the DGT-Cache entry for $G1$ that there is a branch connected to $B2$ and $B5$ forwards the packet to $B2$. Similarly, $B2$ forwards the packet to $B1$ and $B3$. $B3$ forwards the packet to $B4$. Since $B1$, $B3$ and $B4$ contain $G1$'s DGT-Cache entry with non-zero RC value, they all broadcast the packet to each group member via radio interface.

Note that the tracking idea in DGT is quite similar to the idea of *Forwarding Pointer* for mobility management [31]. Forwarding Pointer is also based on a distributed data structure storing pointers to the locations of each user in various nodes. These pointers are updated as users move in the network. Directory servers are used for storing the pointers, and to localize the update operations on pointers, some of the pointers are allowed to be inaccurate. Instead of tracking a single mobile host, DGT tracks all the members in a group by using the caching mechanism in each base station. Moreover, multicast routing among group members is integrated in DGT. Therefore, the cached information for a group must be accurate for correct multicast delivery.

2.2 Constructing DGT-Tree

In DGT, the gateway in the Cellular IP network is responsible for group membership management as in GBMP-RO and MTMP. In order to support group communications, the gateway maintains a *Group Membership Table* to keep track of the membership information for each multicast group. 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. When a mobile user wants to join a group, the mobile host sends an *IGMP-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. To leave a multicast group, the mobile host sends out an *IGMP-Leave* request and the gateway removes the IP address of the mobile host from the member list of the group.

Since the gateway is responsible for group membership management, a mobile user wants to create a new group has to sent a group initiation request with the ID of the group to the gateway. After the gateway successfully creates the new group, identification of the initiator of the group is recorded in the group membership table. The DGT-Tree for the new group at this time contains a single base station that the initiator is connected to, and the DGT-Cache for the group created by the base station is (*Group ID*: *Null* : *RC*=1).

When a mobile user wants to join a group, it sends an *IGMP-Join* message to the gateway as mentioned above. If the join request is granted, the DGT-Tree for the group must be extended to include the current location of the new member. The current base station of the new member must grow branches until the new branches are connecting to the group's DGT-Tree. The problem is how does the new member know the correct direction in which new branches should grow? To provide the correct direction for tree growing, the gateway asks one of the group members (e.g. the initiator) to report its current base station (as the target base station for tree growing) to the new member. The new member then invokes *DGT-Tree-Grow* process toward the target base station. Another problem arises: what if the member providing the target base station moves to another base station during the DGT-Tree-Grow process such that the target base station is no longer on the group's DGT-Tree? The problem can be solved easily as explained in the following. When a base station is being removed from a group's DGT-Tree, we do not immediately clear the corresponding DGT-Cache entry; instead we merely mark the cache entry as invalid and set a garbage collection timer that is longer than the maximum time to finish DGT-Tree-Grow process. Thus, even if the target base station is not on the group's DGT-Tree, we can follow the invalid cache entry to re-connect the target base station to the group's DGT-Tree. One example of DGT-Tree-Grow process is given in Fig. 2.

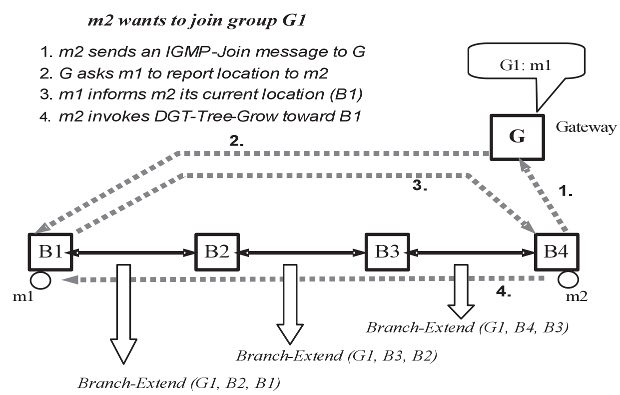


Fig. 2 E.g. DGT-Tree-Grow process.

In Fig. 2, the first step for mobile user $m2$ to join group $G1$ is to send an *IGMP-Join* message to the gateway. After granting the request, the gateway asks the only member $m1$ of group $G1$ to report its current base station ($B1$) to $m2$. When receiving the IP address of $m1$'s current base station, $m2$ invokes DGT-Tree-Grow process started from $m2$'s current base station $B4$ to the target base station $B1$. As shown in Fig. 2, DGT-Tree-Grow process is a series of branch creation operations. The operation of creating an individual branch between two base stations is called *Branch-Extend* operation in the paper. Branch-Extend operation involves updating corresponding DGT-Caches in the base stations on both ends of the branch. DGT-Tree-Grow process stops when the newly created branch has connected to the previous DGT-Tree, i.e., the newly created branch has connected to a base station that is already on the DGT-Tree. Algorithms of DGT-Tree-Grow process and Branch-Extend operation are shown in Fig. 3.

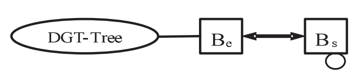
DGT-Tree-Grow Process

Description: started from base station B_s (for mobile user m) to target base station B_z, creating branches to connect B_s to DGT-Tree of group G_i

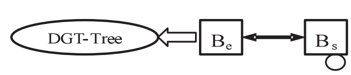
Notation: DGT-Cache for G_i at B_s is denoted by $B_s.G_i$
RC field in $B_s.G_i$ is denoted by $B_s.G_i.RC$
Branch information field in $B_s.G_i$ is denoted by $B_s.G_i.BranchInfo$

{
Case 1: B_s *is already on* G_i*'s* DGT-Tree

{
Set $B_s.G_i.RC$ += 1
Stop DGT-Tree-Grow Process
}
Case 2: B_s *is not already on* G_i*'s* DGT-Tree
{
Assume next base station for tree growing is B_e
(B_e is obtained by static routing from B_s *to* B_z *or by the invalid cache entry of* G_i*)*
Sub-case 2.1 B_e *is already on* G_i*'s* DGT-Tree



{
Call ***Branch-Extend (m, G_i, B_s, B_e)***
Stop DGT-Tree-Grow Process
}
Sub-case 2.2: B_e *is not on* G_i*'s* DGT-Tree



{
Call ***Branch-Extend (m, G_i, B_s, B_e)***
Repeat **Case 2** (new $B_s = B_e$)
}
}
}

Branch-Extend (m, G_i, B_s, B_e)

Description: creating a branch from B_s to B_e for mobile user m in group G_i

Notation: DGT-Cache for G_i at B_s is denoted by $B_s.G_i$
RC field in $B_s.G_i$ is denoted by $B_s.G_i.RC$
Branch information field in $B_s.G_i$ is denoted by $B_s.G_i.BranchInfo$

{
/*** at B_s ***/
Create $B_s.G_i$ if it does not exist
$B_s.G_i.RC$ += 1 if mobil e user m is connected to B_s
$B_s.G_i.BranchInfo$ += B_e
/*** at B_e ***/
Create $B_e.G_i$ if it does not exist
$B_e.G_i.BranchInfo$ += B_s
}

Fig. 3 Algorithms: DGT-Tree-Grow and branch-extend.

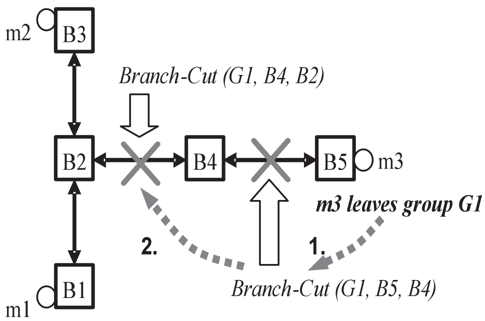


Fig. 4 E.g. DGT-Tree-Trim process.

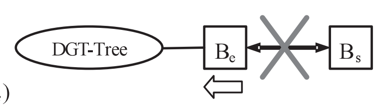
On the other hand, another process called *DGT-Tree-Trim* process is invoked when a member leaves its group. As illustrated in Fig. 4, DGT-Tree-Trim process removes branches ($B5 - B4$ and $B4 - B2$) on the DGT-Tree that are no longer needed after group member $m3$ has leaved the group. The operation of removing a single branch from a DGT-Tree is called *Branch-Cut* operation in the paper. Algorithms of DGT-Tree-Trim process and Branch-Cut operation are shown in Fig. 5.

DGT-Tree-Trim Process

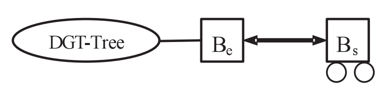
Description: started from base station B_s on the leaving of mobile user m to trim unnecessary branches on group G_i's DGT-Tree (before invoking the process, $B_s.G_i.RC$ has been decreased by 1, *i.e.* $B_s.G_i.RC$--)

Notation: DGT-Cache for G_i at B_s is denoted by $B_s.G_i$
RC field in $B_s.G_i$ is denoted by $B_s.G_i.RC$
Branch information field in $B_s.G_i$ is denoted by $B_s.G_i.BranchInfo$

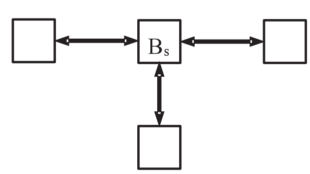
{
Case 1: B_s is a leaf node on the DGT-Tree (only one *base station ID* in $B_s.G_i.BranchInfo$)
{
(Assume B_e is the only base station in $B_s.G_i.BranchInfo$)
If $B_s.G_i.RC$ equals 0 (B_s is no longer needed)
{
Call ***Branch-Cut*** **(*G_i*, *B_s*, *B_e*)**
Repeat DGT-Tree-Trim Process (new $B_s = B_e$)
}



Else ($B_s.G_i.RC$ >= 1)
Stop DGT-Tree-Trim Process
}



Case 2: B_s is a non-leaf node
{
Stop DGT-Tree-Trim Process
}
}



Branch-Cut **(*G_i*, *B_s*, *B_e*)**

Description: remove the branch between B_s and B_e from G_i's DGT-Tree

Notation: DGT-Cache for G_i at B_s is denoted by $B_s.G_i$
RC field in $B_s.G_i$ is denoted by $B_s.G_i.RC$
Branch information field in $B_s.G_i$ is denoted by $B_s.G_i.BranchInfo$

{
/*** at B_s ***/
Invalidate $B_s.G_i$ and set a timer for garbage collection
/*** at B_e ***/
Remove B_s from $B_e.G_i.BranchInfo$ (i.e. $B_e.G_i.BranchInfo$ -= B_s)
}

Fig. 5 Algorithms: DGT-Tree-Trim and branch-cut.

3. Maintaining DGT-Tree

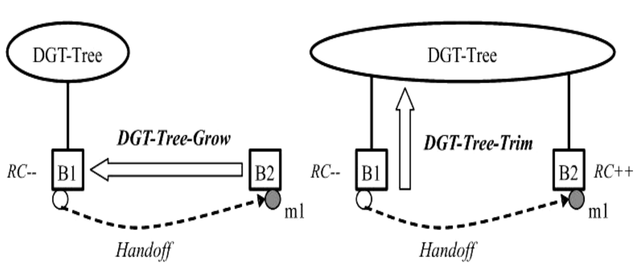
3.1 Dealing with Mobility

The DGT-Tree of a group has to adapt to the mobility of its mobile members, i.e. after the successful handoff of a mobile member to another base station, the group's DGT-Tree should be updated to match with the new situation. In order to provide necessary information for updating DGT-Tree, a mobile member after handoff informs the new base station of the old base station's ID and informs the old base station of the new base station's ID.

As illustrated in Figs. 6(a) and (b), there are two cases for updating the DGT-Tree after the handoff of a group member. In Fig. 6(a), mobile member $m1$ of a group moves from base station $B1$ to another base station $B2$ and $B2$ is not on the group's DGT-Tree (i.e. no DGT-Cache entry existed for the group in $B2$). $B2$ invokes DGT-Tree-Grow process to perform a series of Branch-Extend operations to target base station $B1$. On the other hand shown in Fig. 6(b), if $B2$ is already on the group's DGT-Tree, there is no need for DGT-Tree-Grow process. But $B1$ has to check if the handoff resulting in some unnecessary branches in the DGT-Tree. Thus, $B2$ asks $B1$ to invoke DGT-Tree-Trim process to cut unnecessary branches.

3.2 Consistency of DGT-Cache

As presented in previous paragraphs, two mechanisms to maintain DGT-Tree for handoff, joining, or leaving of a group member are DGT-Tree-Grow and DGT-Tree-Trim processes. Each of them uses Branch-Extend operation or Branch-Cut operation for updating DGT-Tree. Note that a branch in the DGT-Tree is bi-directional and both sides (base stations) of the branch maintains a DGT-Cache entry for the group. Therefore, in order to maintain the consistency of DGT-Cache data during DGT-Tree-Grow or DGT-Tree-Trim processes, updating the DGT-Cache entries for a branch in both sides of base stations must be atomic. That is, there must not be two or more processes concurrently updating the DGT-Cache entries for a branch. One possible solution to provide atomicity of updating DGT-Cache in related base stations of a branch is to lock corresponding DGT-Cache entries before updating them. Moreover, in order to get rid of deadlock situations, a process must concurrently lock the DGT-Cache entries of a branch in both base stations. If concurrent locking fails, the process has to wait a random time before performing another locking.



(a) New base station is not on DGT-Tree. (b) New base station is on DGT-Tree.

Fig. 6 DGT handoff scheme.

3.3 Security Issues

The objectives of multicast security [32] are to preserve authentication and secrecy for all group communications so that only registered senders can send packet to the group and only registered receivers can read packets sent to the group. In addition to the authentication mechanism controlling the access of the wireless link in each base station, data encryption is required to enforce message secrecy for a multicast group. This requires a group key management solution [33]–[35] to distribute and maintain cryptographic keys with registered group members. Similarly, cryptographic authentication schemes are necessary to ensure that registered receivers can verify that received packets come from registered senders.

In order to support secure group communications in DGT, the gateway should act as the controller of group key management since it is the controller of group membership. Each base station acts as a security agent instructed by the gateway. Only authenticated members can update the DGT-Cache (due to either join/leave or handoff) in each base station for the group. Multicast packets should be encrypted before sending out by the authenticated sender. The mechanism for supporting secure group communications is beyond the scope of the paper†. For a good survey of major research challenges, future trends, and directions of multicast security, please refer to the work of Judge and Ammar [36].

3.4 Dealing with Members Outside the CIP Network

The proposed DGT scheme is mainly focused on intra-CIP group communications, in which all group members are within a single CIP network. In the case of some group members outside the CIP network, a so-called *macro mobility multicast routing protocol* (e.g. some multicast extensions of Mobile IP) operating over the Internet must be adopted. Therefore, in this case, the gateway must be always on the DGT-Tree of the group. More specifically, to DGT scheme, the gateway acts as the representative (agent) for the members outside the CIP network and operates just like other regular nodes (base stations) on the DGT-Tree for the group except it also has to handle the macro mobility part. The multicast protocol for the macro mobility domain is beyond the scope of the paper.

†For the reason of simplicity, in this paper we merely introduce basic concepts of security in Cellular networks. Most of the security algorithms for group communications can be applied in our approach.

4. Performance Evaluation

4.1 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 can 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.

To evaluate the performance of DGT, we create 1,000 groups and build corresponding DGT-Tree with a given group size. Group members are randomly selected from mobile hosts in the network in the beginning of the simulation. Total run time in the simulation is 600 time slots. Four performance criteria are defined for comparing DGT with other schemes:

(1) Average transmission cost
(2) Relative load of each wired link in the Cellular IP network at the end of the simulation
(3) Average length of "the longest transmission path in a group"
(4) Average cache size (bytes) per group for supporting DGT operation

The transmission cost is defined as the total number of data packets generated in the Cellular IP network to transmit a packet to all group members. Relative load of each wired link is calculated as follows. The number of data packets transmitted in each wired link is recorded during the simulation. At the end of the simulation, the load of a wired link is computed as the number of packets transmitted in the link divided by the maximum number of packets among all wired links. That is, the load of the link with the maximum number of packets transmitted is set to 1, and the load of other links is calculated by normalizing the number of packets to the maximum number of packets.

The average length of "the longest transmission path in a group" indicates another property of the multicast routing. The longest transmission path in the multicast routing tree reflects the finish time for a single packet transmission. Therefore, the shorter the longest transmission path, the better the routing scheme. Lastly, the average cache size per group for supporting DGT operation is the total number of bytes of DGT-Cache per group. In the simulation, the number of bytes for each fields of DGT-Cache (please refer to Fig. 1(a)) is assigned as follows: *Group ID*: 4 bytes (an IP class D address), *Branch information*: 1 byte for each branch (i.e. at most 4 bytes in the case of the mesh network), *Radio user count*: 1 byte. Thus, there are at most 9 bytes of an entry in DGT-Cache for a group.

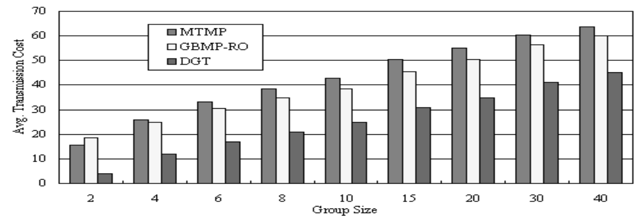


Fig. 7 Average transmission cost. (MoveProb = 0.5)

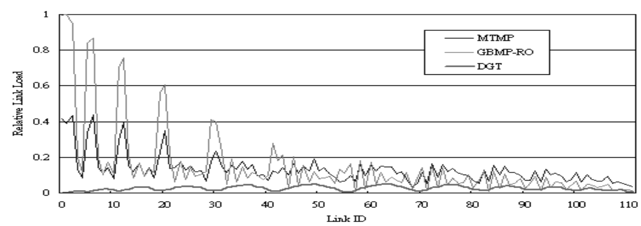


Fig. 8 Relative link load at 600th time slot. (Group size = 2, MoveProb = 0.5)

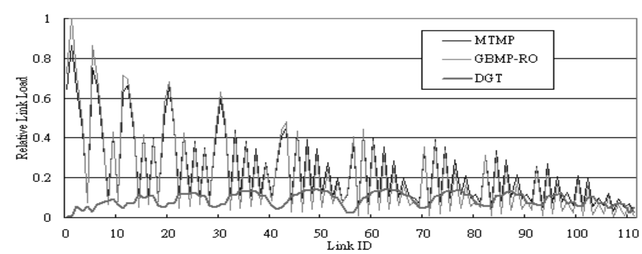


Fig. 9 Relative link load at 600th time slot. (Group size = 10, MoveProb = 0.5)

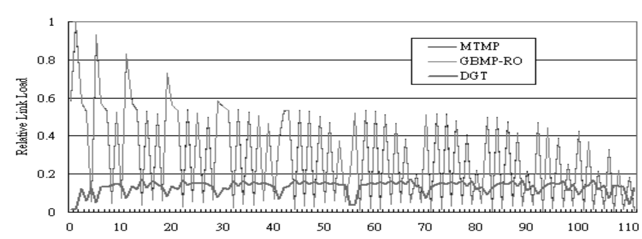


Fig. 10 Relative link load at 600th time slot. (Group size = 40, MoveProb = 0.5)

4.2 Simulation Results

Average costs of group communications for MTMP, GBMP-RO, and DGT are displayed in Fig. 7. It shows that proposed DGT outperforms the other two protocols in terms of average transmission cost. Moreover, Fig. 7 also shows that DGT can save up to 50% of the transmission cost over GBMP-RO for group size under 4. For a large group size (e.g. 40), 25% of the transmission cost can be saved by DGT.

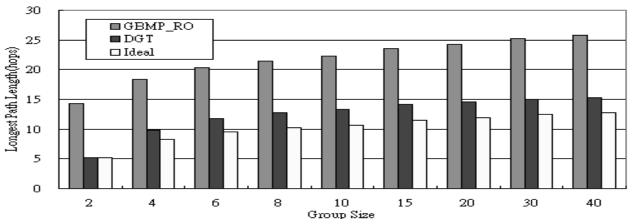


Fig. 11 Average length of the longest transmission path. (MoveProb = 0.5)

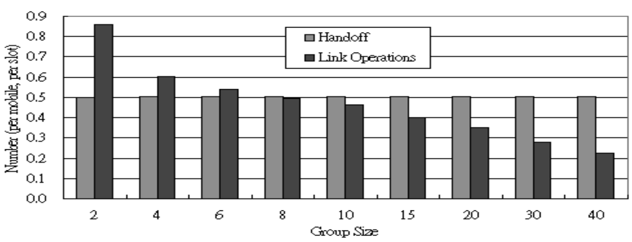


Fig. 12 Average number of link operation (per mobile host per slot) in DGT. (MoveProb = 0.5)

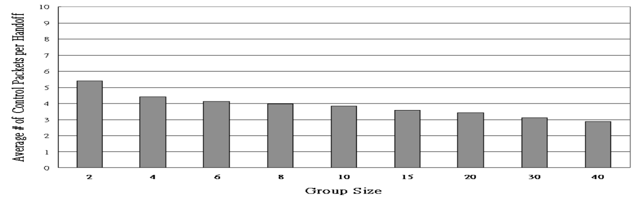


Fig. 13 Average number of control packets per handoff in DGT. (MoveProb = 0.5)

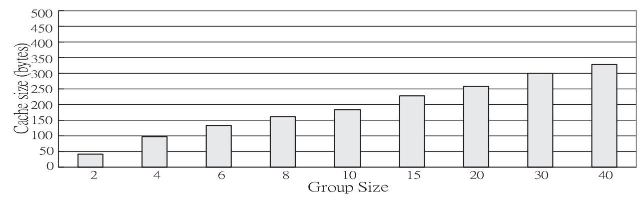


Fig. 14 Total number of bytes of DGT-Cache at all base stations for a single group. (MoveProb = 0.5)

Figures 8–10 display the relative load of each wired link in the network for different group communications schemes with group sizes 2, 10, and 40 respectively. The assignment rule for the index of each link is that a closer link to the gateway gets a smaller index. Load unbalance can be found in GBMP-RO as well as MTMP since closer links to the gateway get much more load than other links. These figures demonstrate the better effect of load balancing as well as the efficiency of group communications by DGT. Please note that since the simulation results for different *MoveProb* values are quite close, we only display the case of *MoveProb* = 0.5 in the paper.

Figure 11 shows the *average length of "the longest transmission path in a group*" for DGT and GBMP-RO respectively, and the ideal case (i.e. the shortest path length of two farthest members in a group) is also displayed in the figure for comparison. The longest transmission path in DGT is about 40% shorter than the path length in GBMP-RO and about 25% longer than the ideal case (the optimal value), which implies a good property of the multicast tree built by DGT. Moreover, as an example of the ideal case for path length, *MOSPF* (*Multicast Open Shortest Path First Protocol*) can give the shortest path between two group members. However, the tree construction and maintenance cost in MOSPF is a lot more than DGT since the number of MOSPF trees (source-based tree) for a group depends on the size of the group but there is only one tree for a group in DGT.

To investigate the overhead of DGT in dealing with the handoff of a group member, we calculate the average number of branch operations (Branch-Extend, Branch-Cut) per mobile host in a time slot for a given *MoveProb*. As shown in Fig. 12, the average number of handoff per mobile host in a time slot is equal to the value of *MoveProb*. The average number of DGT branch operations is going down when the group size is getting large, since the probability that both the new and the old base stations of the handoff are in the group's DGT-Tree (i.e. except the mobile host being handoff, there are other group members in both base stations) is high for a large group. In the case of both the new and the old base stations being in the group's DGT-Tree, no branch operations are required. For the group size larger than 8, the average number of DGT branch operations is even smaller than the average number of handoff that implies the good scalability of DGT. Moreover, Fig. 13 shows the average number of control packets generated in the network for performing branch operations after each handoff. Since the control packet is much shorter than regular data packets, DGT introduces moderate signaling overhead in the network. The value of the average number of control packets can be further reduced if the signaling information of DGT operations can be piggybacked in the control packets for handoff control.

Figure 14 shows the total number of bytes of DGT-Cache at all base stations for a single group with different group sizes. In average, DGT requires 329 bytes of DGT-Cache for a group with 40 members. It implies that the total cache size will be 329 kbytes for supporting up to 1000 groups of size 40, and the cache size at individual base station for 1000 groups is only about 7 kbytes, which is moderate from the viewpoint of memory requirement.

5. Conclusion

In this paper, a novel location management scheme and multicast routing protocol for group communications in Cellular IP networks are proposed. The location management scheme for a group of members is called Distributed Group Tracking (DGT), which is based on location tracking of each member in a group. In DGT, Base stations track each member of a group and build a share routing tree called DGT-Tree for the group in a distributed manner. Transmission of multicast packets among group members is along the group's DGT-Tree. Mechanisms for building the DGT-Tree for a group and updating the DGT-Tree when handoff of a group member occurs are proposed. Simulation study has demonstrated that a better performance can be achieved by DGT over the gateway-based counterpart in terms of transmission cost as well as link load balance. Moreover, the average number of DGT branch operations decreases as the group size increases, showing the good scalability of the DGT scheme. Lastly, the average number of control packets generated after each handoff of group members and the cache requirement for performing DGT operations have demonstrated the moderate overhead of using DGT.

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