Route Optimization and Location Updates for Mobile Hosts *

Weidong Chen Eric Lin
Department of Computer Science & Engineering
Southern Methodist University
Dallas, Texas 75275-0122
{wchen,ecl}@seas.smu.edu

Abstract

Mobile hosts in a wireless network can move from one location to another while communicating with other hosts. A challenge is to provide seamless network access for mobile hosts and, at the same time, to retain compatibility with existing network protocols and applications. This paper addresses the issue of route optimization in IP mobility support that provides mobile handoff and "triangle" routing to mobile hosts through their home agents. We combine IP mobility support with hierarchical dynamic routing protocols OSPF and BGP. Existing mechanisms of authentication, incremental route propagation, and address aggregation can be used for efficient and secure propagation of location updates of mobile hosts. The geographical locality of consecutive mobile handoffs fits well with hierarchical dynamic routing protocols. No changes are required on fixed hosts or on routers that do not handle mobile hosts directly.

1. Introduction

The trend towards tetherless communications and the advancing technology of laptop and notebook computers induce a growing demand for mobile and nomadic computing. Unlike fixed hosts in a wired network, mobile hosts in a wireless network can move from one location to another while maintaining continuous network connections. A challenge is to provide seamless network access for mobile hosts and, at the same time, to retain compatibility with existing network protocols and applications.

The sheer number of existing hosts and installed network applications makes compatibility a practical necessity. This requirement has several implications. First, fixed hosts on a wired network that are not involved in mobility support should not have to be modified in order to communicate with mobile hosts. Second, each mobile host should have a permanent address as its identity, even though its location may change from time to time. This is necessary so that high level protocols that use host addresses do not have to be modified [5]. Third, the mapping between permanent identities of mobile hosts and their current locations has to be maintained so that packets can be routed correctly to mobile hosts. This mapping needs to be updated whenever a mobile host changes its location.

The Internet draft for IP mobility support [12] provides mobility through "triangle" routing. A packet for a mobile host is routed to the home network of the mobile host as identified by its permanent IP address. The home network tracks the current location of the mobile host and forwards the packet to the network where it is currently located. This "triangle" routing through the home network of a mobile host is almost always suboptimal.

A major advantage with IP mobility support [12] is its compatibility with existing network protocols and applications. Only mobile agents and mobile hosts need to be modified at the IP and ARP level. A similar model has been adapted by CDPD for data communications using existing cellular channels [1]. However, the compatibility is achieved at the expense of routing efficiency to mobile hosts.

Our approach is to combine IP mobility support with hierarchical dynamic routing protocols, including OSPF [9] for interior gateway routing and BGP [13] for exterior gateway routing. While the IP mobility support continues to provide a basic model of mobile internetworking, with the default triangle routing through the home networks of mobile hosts, route optimization is achieved by propagating location updates of mobile hosts as host route changes.

*Work supported in part by the Texas Higher Education Coordinating Board, Advanced Technology Program Grant 003613-019.

This approach has several advantages. First, compatibility with existing network protocols and applications is preserved since only mobile support routers have to be changed to convert location updates of mobile hosts into advertisements of host route changes. The implementation of an IP based mobile internetworking protocol can be simplified since it does not have to deal with route optimization. Second, existing mechanisms in dynamic routing protocols can be used directly for location propagation, including reliable propagation, incremental routing table update, authentication, and address aggregation. Third, the geographical locality of consecutive mobile handoffs fits well with hierarchical dynamic routing protocols.

The rest of the paper is organized as follows. Section 2 introduces IP mobility support in which packets for mobile hosts are routed transparently to their home networks and then tunneled to their current locations. Section 3 reviews the Internet routing protocols OSPF (for intra-autonomous system routing) and BGP (for inter-autonomous system routing). Section 4 presents route optimization of IP mobility support using OSPF and BGP, and analyzes the communication, processing and storage requirements for route optimization. Section 5 concludes with a discussion of related work.

2. IP Mobility Support

The Internet draft for IP mobility support [12] specifies a basic model of mobile internetworking that is shared by most IP based protocols. It is compatible with the IP protocol and requires no changes on fixed hosts that communicate with mobile hosts or on mobile hosts above the IP level.

A *mobile host* (MH) is a host that is connected to the wired network through a wireless interface and that can maintain network connections even when it roams into another network. A *stationary host* (SH) is a host whose attachment to a network is fixed. A *mobile agent* (MA) is a router that communicates with mobile hosts through a wireless interface and that is also attached to the wired network.

A mobile host is assigned a permanent IP address, which also identifies the home network of the mobile host. A mobile agent in the home network is called a *home agent* of the mobile host. When a mobile host is at home, packets to the mobile host are routed as in regular IP to the home network and sent to the mobile host through a home agent.

When a mobile host roams into a foreign network, it communicates with other hosts through a *foreign agent* – a mobile agent in the foreign network. In this case, the permanent IP address of the mobile host no longer indicates its current location. A *care-of address* is used to represent the current location, which can be the IP address of the foreign agent handling the mobile host.

A mobile agent keeps a list of all mobile hosts that consider the mobile agent as its home agent. For each mobile host away from home, the home agent maintains a binding between the permanent IP address and the current care-of address of the mobile host. A mobile agent also keeps a list of all visiting mobile hosts and their corresponding home agent addresses.

Figure 1 indicates the "triangle" routing when a stationary host $\mathcal{S}$ sends packets to a mobile host $\mathcal{M}$ that is away from home, where $\mathcal{A}_h$ is the home agent and $\mathcal{A}_f$ is the current foreign agent for $\mathcal{M}$. A packet to $\mathcal{M}$ has the permanent IP address of $\mathcal{M}$ as the destination address and is routed as in regular IP to the network of the home agent $\mathcal{A}_h$. $\mathcal{A}_h$ realizes that $\mathcal{M}$ is away from home and forwards the packet to the care-of address, namely $\mathcal{A}_f$. The foreign agent $\mathcal{A}_f$ then sends the packet through the wireless interface to $\mathcal{M}$. The packet forwarding by the home agent $\mathcal{A}_h$ can be done using IP-inside-IP Encapsulation (IPIP) [5]. Notice that packets from $\mathcal{M}$ to the stationary host $\mathcal{S}$ follow an optimal route (as defined by the Internet routing protocols).

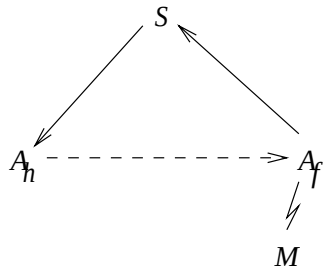

Figure 1. Triangle routing to mobile hosts

When a mobile host is switched on or moves into a network, it should register with its home agent to update its binding. It is assumed that a mobile host can discover a foreign agent by either receiving a beacon signal from the foreign agent or through an ICMP Router solicitation protocol [12]. The following registration messages are sent when a mobile host registers with its home agent:

1. The mobile host sends a registration request to the foreign agent, containing its permanent IP address, its home agent address, and a care-of address;

2. The foreign agent relays the request to the home agent;

3. The home agent grants or denies the service and

sends a registration reply back to the foreign agent;

4. The foreign agent relays the registration reply to the mobile host.

Appropriate authentication mechanisms are included in registration messages for security. A life time is associated with each binding and with each visitor entry so that they will automatically expire after a certain period of time if they are not renewed or updated. A life time of zero indicates de-registration.

At the data link level, the Address Resolution Protocol (ARP) performs the translation of an IP address in a network into a corresponding link level address. When a mobile host moves away from home, its home agent should perform a gratuitous ARP so that the ARP cache entry for the mobile host in other nodes in the home network can be updated. The home agent also performs proxy ARP replies for the mobile host.

3. Internet Routing Protocols

A major advantage with IP mobility support is its compatibility with existing applications since it requires changes only on mobile agents and on mobile hosts at the IP and ARP level. The compatibility is realized at the expense of routing efficiency, due to the fact that all packets destined to mobile hosts away from home are routed through their home agents. We propose route optimization for mobile hosts using existing Internet routing protocols such that location updates can be propagated as route changes. This section reviews the Internet routing protocols, especially OSPF [9]. Route optimization is presented in the next section.

The Internet routing has a hierarchical structure. At the highest level is the Internet backbone that connects Autonomous Systems. The Border Gateway Protocol (BGP) [13] has been recommended as an inter-Autonomous System routing protocol for the Internet backbone.

An Autonomous System (AS) is a set of routers under a single administrative control, which appears to other ASs to have a single coherent interior routing plan and presents a consistent picture of which networks are reachable through it[9]. Certain routers inside an AS are identified as AS boundary routers that represent the AS to the Internet backbone and advertise AS external routes into the AS. The Open Shortest Path First (OSPF) protocol has been recommended as an Internal Gateway Protocol for a single AS [9].

A collection of contiguous networks and hosts, together with the routers having interfaces to any of the included networks, is called an area [9]. The backbone of an AS consists of all the remaining networks not contained in any area, their attached routers and routers that are attached to multiple areas. (The backbone of an AS itself is treated as a separate area.) Area boundary routers are responsible for representing an area to the AS backbone and advertising external routes into the area. Areas such as those with a single default router for external traffic can be classified as "stub" areas, in which case external routes are not flooded into the area.

An area may contain different kinds of physical networks, such as point-to-point and broadcast networks. A broadcast network with multiple routers elects a Designated Router and a Backup Designated Router. The Designated Router of a network originates a network link on behalf of the network. The notions of "stub" areas and Designated Routers are used to provide isolation of network topology information and to reduce the network traffic for route advertisements.

OSPF is a link state routing protocol based upon SPF [8]. Each area runs a separate copy of the basic SPF routing algorithm. All routers attached to the same area have the same link state database, which is essentially a graph whose nodes are routers and networks. An area border router may have multiple link state databases, one for each area to which it is attached, including the AS backbone.

The link state database of each area is built out of link state advertisements. For intra-area routing, there are two kinds of link state advertisements — router links and network links. Each router originates, for each area it belongs to, a router link advertisement, indicating all its connections to networks and other routers. A network link advertisement is originated by its Designated Router, indicating all routers that are connected to the network. These advertisements are flooded throughout an area only.

For inter-area routing within an AS, summary links are originated by area border routers and are flooded into an area, provided that the area has not been configured as a "stub" area. Each summary link indicates a route to a single destination that is external to the area, but still within an AS. The destination can be a network or an AS boundary router.

For destinations external to an AS, AS external links are originated by AS boundary routers. Each AS external link indicates a route to an AS external destination. AS external links are flooded throughout the entire AS.

OSPF has four levels of routes — intra-area, inter-area, Type 1 AS external and Type 2 AS external routes. Intra-area routes are the most preferred, followed in order by inter-area, Type 1 AS external and

Type 2 AS external routes.

Routing traffic in OSPF is sent as IP packets with protocol number 89 [9]. Figure 2 shows the format of the OSPF packet header. All OSPF packets are associated with a single area, and most will travel a single hop only, with Router ID as the source of the packet.

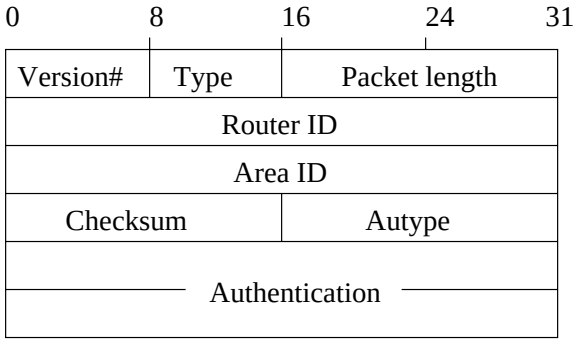

Figure 2. The OSPF packet header format

There are five types of OSPF packets indicated by Type in the OSPF packet header.

Type	Description
1	Hello
2	Database Description
3	Link State Request
4	Link State Update
5	Link State Acknowledgment

The Hello packets are sent periodically to establish and maintain the adjacency relationship between routers. When an adjacency is initialized, a router sends the Database Description packets to indicate to the neighbor what links are in its link state database. The neighbor sends the Link State Request Packets back to request detailed information for links that are out of date in its link state database. The Link State Update packets implement the flooding of link state advertisements, which are acknowledged by the Link State Acknowledgment packets.

Each Link State Update packet has an OSPF header with Type 4, followed by the number of link state advertisements and all the link state advertisements in sequence. Each link state advertisement begins with a common 20 byte header (Figure 3).

Link state advertisements that have the same LS type, Link State ID, and Advertising Router are considered instances of the same link. There are five different types of links as indicated by LS type.

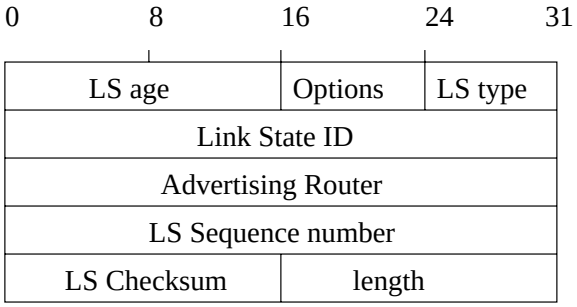

Figure 3. The link state advertisement header

LS type	Description
1	Router links
2	Network links
3	Summary link (IP network)
4	Summary link (AS Boundary Router)
5	AS external link

For router links, Link State ID and Advertising Router are both the OSPF Router ID of the router. A network link is originated by the Designated Router of the network and its Link State ID is the IP address of the network. In both summary links to IP networks and AS external links, the Link State ID is the IP address of the destination network. Routing tables are updated incrementally when summary links or AS external links are received.

4. Route Optimization

Several approaches have been proposed to improve routing efficiency, but require changes to stationary hosts or routers for maintaining location caches, thereby compromising the compatibility with existing applications [3, 7, 10]. This section presents route optimization using hierarchical dynamic routing protocols, especially the area configuration of mobile agents and mobile hosts, route changes due to location updates, and propagation of location updates.

4.1. Area Configuration

In OSPF an AS is composed of several areas that are all connected to the AS backbone. Mobile agents are assumed to speak OSPF for intra-AS routing. The connections between mobile agents and mobile hosts can be viewed as host routes since each individual mobile host has the freedom to roam from one location to another. The area configuration of mobile agents and mobile hosts affects how location updates are advertised as route changes and how they are propagated.

There are at least two possibilities. One is that mobile agents and the attached routes to mobile hosts are part of an area that may include other routers and networks. The other is that mobile agents and the attached routes to mobile hosts constitute independent "stub" areas, with all mobile agents serving as area border routers for the area. As we shall see below, the latter configuration allows more efficient propagation of location updates.

In the former configuration, when a mobile host registers with a foreign agent, the foreign agent needs to originate a network link and a router link advertisement to announce the host route change for the mobile host. The router link advertisement must, by definition, list *all* the connections from the foreign agent to other hosts and routers, not just the host route to the mobile host being concerned. Upon receiving network and router links, a router may have to recalculate its entire routing table.

There is another problem with the former configuration. OSPF imposes a minimum time between distinct originations of any particular link advertisement, in order to restrict the amount of routing traffic. The minimum time is MinLSInterval, which is normally set to 5 seconds. Since all router link advertisements of a foreign agent are considered instances of the same link advertisement, the minimum time limit MinLSInterval applies. It means that a foreign agent cannot announce location updates of mobile hosts more often than once per MinLSInterval seconds. This may be a serious limitation, considering that many mobile hosts may come into or leave the wireless network of a mobile agent.

In contrast, the latter area configuration ensures that mobile agents and their connections to mobile hosts and other networks constitute an independent "stub" area, with no routers in the area that are not involved in mobility support. Since all routers in the area are mobile agents, the intra-area propagation of location updates can be accomplished in a flexible manner, e.g., broadcasting [4, 5]. In the special case where each mobile agent and its attached mobile hosts are a separate "stub" area, the intra-area propagation of location updates is trivial. For inter-area propagation of location updates, mobile agents acting as area border routers originate summary links into the AS backbone and other areas that they belong to. Each summary link indicates a route to a single mobile host. An OSPF packet containing only one summary link for a mobile host takes $24 + 4 + 20 + 8 = 56$ bytes. The 24 byte OSPF header can be shared by multiple summary links if they are combined into a single Link State Update packet. Since summary links for different mobile hosts have different Link State IDs, the minimum time limit MinLSInterval applies to each mobile host, instead of to a mobile agent as in the former area configuration. The direct announcement of summary links into the AS backbone allows faster propagation of location updates to other areas and other ASs.

We choose the latter area configuration. For simplicity, we assume that each mobile agent and its attached routes to mobile hosts constitute a "stub" area, with the mobile agent as the sole area border router. If such a configuration leaves the mobile agent disconnected from the AS backbone, virtual links should be established between the mobile agent and AS backbone [9].

4.2. Location Updates as Route Changes

When a mobile host registers with a mobile agent, the location information of the mobile host should be propagated as route changes. We consider link advertisements originated by the home agent $\mathcal{A}_h$, the new foreign agent $\mathcal{A}_f$ and the previous foreign agent $\mathcal{A}_p$ due to the registration of a mobile host $\mathcal{M}$ with $\mathcal{A}_f$.

According to IP mobility support [12], when $\mathcal{M}$ registers with $\mathcal{A}_f$, the following is established if the registration is successful:

- $\mathcal{A}_h$ has a route entry for $\mathcal{M}$ with a forwarding address of $\mathcal{A}_f$;
- $\mathcal{A}_f$ has a visitor entry for $\mathcal{M}$.

Each registration has a *lifetime* associated with it, after which the corresponding entries in $\mathcal{A}_h$ and $\mathcal{A}_f$ may automatically expire. Connection can be maintained by $\mathcal{M}$ sending another registration before the lifetime expires. A value 0 for lifetime in a registration means deregistration. A suggested default value for lifetime is 1800 seconds [12].

The new foreign agent $\mathcal{A}_f$ originates a Link State Update packet containing a new summary link for the visiting mobile host $\mathcal{M}$. The format of the entire OSPF packet is shown in Figure 4, assuming that only the default Type of Service TOS 0 is supported. The metric indicates the cost of the connection from the foreign agent to the mobile host. The summary link indicates a host route to the mobile host by a network mask of `0xffffffff`. The Link State Update packet is flooded into each area that is not classified as a "stub" area and that $\mathcal{A}_f$ belongs to, including the AS backbone.

The home agent $\mathcal{A}_h$ does not originate any announcement of route changes when one of its local mobile hosts $\mathcal{M}$ registers through a foreign agent $\mathcal{A}_f$. There are two reasons. First, the home agent $\mathcal{A}_h$ always maintains a default route to each of its local mobile hosts. If one of its local mobile hosts $\mathcal{M}$ is away

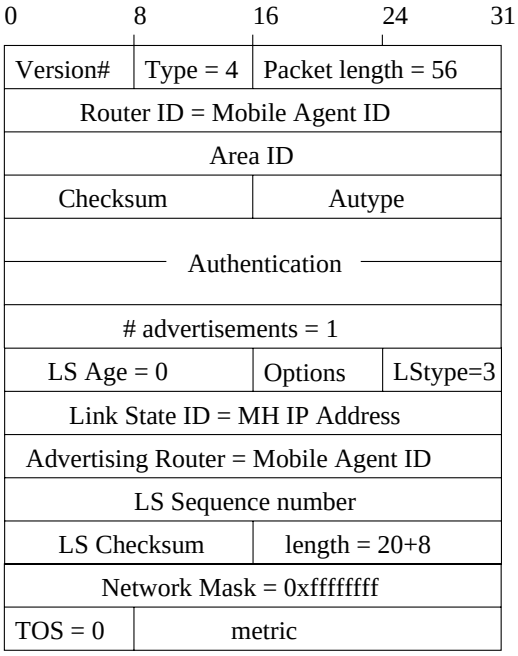

Figure 4. Link state update packet for mobile registration

from home, the default route is through forwarding to the current foreign agent $\mathcal{A}_f$. Due to the "hop-by-hop" routing paradigm in the Internet, the home agent advertises only the routes that it uses itself. For all the local mobile hosts, they are the default routes, which do not have to be advertised due to regular IP routing. Second, even if the home agent $\mathcal{A}_h$ advertises a link to $\mathcal{M}$ with a larger cost because of the extra packet forwarding to $\mathcal{A}_f$, the resulting benefit may be minimal due to the interaction with OSPF and BGP. If the foreign agent $\mathcal{A}_f$ is in the same AS as $\mathcal{A}_h$, then $\mathcal{A}_f$ advertises a more specific link to $\mathcal{M}$. Among routing table entries of the same path type, OSPF always prefers the one that has the longest match. If the foreign agent $\mathcal{A}_f$ is in another AS, AS external links imported from BGP into OSPF have a default OSPF metric type of Type 2 [15]. As we have mentioned before, costs of Type 2 always dominate inter-AS routes.

If the mobile registration of $\mathcal{M}$ is part of a mobile handoff, $\mathcal{M}$ should also de-register from the previous foreign agent $\mathcal{A}_p$. $\mathcal{A}_p$ should continue to retain the connection to $\mathcal{M}$ through the new foreign agent $\mathcal{A}_f$ for a short period of time. First, there may be packets in transit for $\mathcal{M}$ that are being tunneled by $\mathcal{A}_h$ to $\mathcal{A}_p$. These packets should be forwarded to $\mathcal{M}$ through $\mathcal{A}_f$ in order to avoid excessive packet drops. Second, due to the minimum time limit MinLSInterval, $\mathcal{A}_p$ may not be able to announce a summary link for the deletion of its host route to $\mathcal{M}$ immediately. When $\mathcal{A}_p$ cuts off the connection to $\mathcal{M}$, $\mathcal{A}_p$ should flush its summary link advertisement for $\mathcal{M}$ by originating another summary link advertisement for $\mathcal{M}$ with LA Age equal to MaxAge.

4.3. Propagation of Location Updates

Propagating location updates of mobile hosts improves the routing performance to mobile hosts, but it also consumes the network bandwidth, processing time and memory storage of routers. We consider propagation within an AS and among ASs.

Location Propagation within an AS. By configuring each mobile agent and its host routes to mobile hosts into a "stub" area, a mobile agent can advertise location updates of mobile hosts as summary links directly into an AS backbone and areas that are not "stub" areas since the mobile agent also serves as the area border router. This avoids any intra-area delay for location propagation. OSPF supports incremental routing table updates when summary links are received. When a summary link to a network destination N is received, only the routing table entry for N needs to be updated.

When a mobile host comes into the network of a foreign agent, the foreign agent originates a summary link to announce its connection to the mobile host. When the mobile host leaves, the foreign agent originates another summary link with LS Age = MaxAge to flush its connection to the mobile host out of the routing tables. Thus each location update requires two summary link advertisements. In the worst case, each summary link is in a separate Link State Update packet that is 56 byte long. Adding an IP header of 20 bytes, each origination of a summary link for a mobile host takes 76 bytes, and each location update requires 152 bytes for two originations of a summary link.

Consider the graph of all routers in the AS backbone and in areas that are not "stub" areas. A summary link for a connection to a mobile host is propagated to all the routers in the graph. Let d be the mean distance of the graph. Let v be the number of mobile hosts in the AS that are away from home and h be the interval between consecutive location updates of a mobile host. Then the link bandwidth for propagation of location updates within an AS is $O(152 \times d \times v/h)$ bytes per second. As the mean distance d is relatively stable, the link bandwidth for propagation depends the mobility of visiting mobile hosts, where v/h indicates the number of location updates that need to be propagated.

Memory requirements in OSPF are dominated by the size of the link state database. Mobile hosts that are away from home have corresponding summary links. Each summary link is 28 bytes long, plus some support data. So a reasonable estimate of router memory consumed by a summary link is probably 60 bytes. On a mobile handoff, it is possible that there may be two summary links for a mobile host, one by the previous foreign agent and the other by the current foreign agent. Thus the router memory for mobile hosts away from home is about $O(120 \times v)$, where v is the number of mobile hosts that are away from home and that are in the AS.

Location Propagation among ASs. The Internet backbone can be viewed as a graph connecting ASs. BGP is an inter-AS routing protocol [13]. Communications between a pair of BGP speakers use TCP for reliable transfer of route information. BGP does not require periodic refresh of the entire BGP routing table. Incremental updates are sent as the routing tables change.

Route changes are sent as UPDATE messages. An UPDATE message advertises a single feasible route to a peer and/or withdraws multiple infeasible routes from services. Withdrawn routes are represented by a list of IP address prefixes whose routes are taken out of service. A feasible route consists of Network Layer Reachability Information and Path Attributes. The Network Layer Reachability Information is a list of IP address prefixes for which a route is being advertised. The Path Attributes contain, among other information, the following fields:

- ORIGIN that indicates the AS that originates the associated routing information;
- AS_PATH that identifies the ASs through which routing information carried in the UPDATE message has passed; and
- NEXT_HOP for the IP address of the border router that should be used as the next hop to the destinations listed in the Network Layer Reachability Information.

BGP imposes two timers to control the routing traffic. The parameter MinRouteAdvertisementInterval is the minimum time that must elapse between advertisements of routes to a particular destination from a BGP speaker. It applies, on a per destination basis, to advertisements (to BGP speakers in other ASs) of feasible routes that are learned from BGP speakers in neighboring ASs. To avoid long-lived black holes, it does not apply to explicit withdrawal of infeasible routes. The default value for MinRouteAdvertisementInterval is 30 seconds. The parameter MinASOriginationInterval is the minimum time between consecutive advertisements of UPDATE messages by an AS border router that reports changes in its AS. Its default value is set to 15 seconds.

For mobile hosts that are away from their home networks, but are still within their home ASs, their routes can be aggregated together with the routes for their home networks as far as inter-AS routing is concerned.

For mobile hosts that are away from their home ASs, their host routes have to be advertised separately. Let R be the number of mobile hosts that are roaming in foreign ASs. The extra memory requirement due to mobile hosts is

$$O(R \times K)$$

where K is the number of connections a BGP speaker has with other BGP speakers. The link bandwidth for incremental updates of route changes of mobile hosts is

$$O(C \times M)$$

where C is the number of mobile handoffs across ASs and M is the mean AS distance of the Internet (in terms of the number of ASs). Since an AS normally consists of multiple areas, we expect that mobile hosts stay in an AS for a longer period of time. This is consistent with the current default parameter setting of MinLSInterval (5 seconds) in OSPF and MinASOriginationInterval (15 seconds) in BGP.

Even if a mobile host stays within an AS for a longer period of time, it is possible that the mobile host may move around within an AS frequently. Suppose that a mobile host $\mathcal{M}$ stays within an AS long enough so that its location information has been propagated to other ASs in the Internet backbone. Then frequent location updates of $\mathcal{M}$ within an AS will not cause any additional inter-AS location propagation for $\mathcal{M}$. Any packets for $\mathcal{M}$ will be routed efficiently to the AS in which $\mathcal{M}$ is located. Within the AS, the minimum interval of MinLSInterval seconds (with default value 5) imposed by OSPF on originating distinct instances of the same link state advertisement limits the amount of routing traffic.

5. Related Work

Several IP based protocols have been developed for mobile internetworking [3, 4, 6, 7, 10, 11, 14]. To avoid "triangle" routing to mobile hosts, various mechanisms of route optimization have been proposed. In [6, 11], IP's Loose Source Routing option was used to achieve

optimal routing to mobile hosts. Unfortunately existing implementations may drop IP options or do not implement the Loose Source Route option correctly. In the Virtual Internet Protocol (VIP) [14], every host and router participates in route optimization by maintaining a location cache. Stationary hosts on a wired network are treated as special cases whose identity and current location are always the same. In [4, 5], all mobile hosts belong to a *mobile subset*, which appears as a single subset to the rest of the routing architecture. Packets for mobile hosts are routed to nearby mobile agents as in regular IP. Within a campus area, broadcasting is used to find the current location of a mobile host. For wide area mobility, only "triangle" routing is used. In [10], a notion of cache agents is introduced so that hosts that wish to optimize their own communication with mobile hosts can maintain a location cache. In [3], a hierarchy of redirection agents is used to forward packets to a mobile host more efficiently, avoiding going through the home agent of the mobile host. A notion of "patron hosts" is used to reduce the overhead of location propagation by notifying only those hosts that actually need to communicate with a mobile host.

Besides routing efficiency and compatibility with existing network protocols and applications, there are some important issues of route optimization, including routing loops, authentication, and limiting route traffic. By combining IP mobility support with existing hierarchical dynamic routing protocols, our approach has several distinctive features. First, no changes are required except on mobile agents and mobile hosts, thereby maintaining compatibility with existing hosts and routers and applications. Second, techniques in hierarchical dynamic routing protocols are used directly for efficient and secure propagation of location updates of mobile hosts, without causing extra routing loops or excessive routing traffic. Third, the hierarchical nature of the Internet routing protocols fits well with the geographical locality of consecutive mobile handoffs of a mobile host. The address aggregation avoids inter-AS location propagation of mobile hosts that are away from home but still within their home ASs.

Both OSPF and BGP include various timers for limiting the amount of routing traffic. To provide further control over the routing traffic due to mobile handoff, we have developed a notion of routing agents that disassociates location propagation from mobile handoffs. This allows flexible policy control over location propagation and route optimization, the details of which will be presented in a separate paper [2].

References

[1] Cellular digital packet data system specification: Release 1.0, July 1993. CDPD, P.O.Box 97060, Kirkland, MA 98083.

[2] W. Chen, E. Lin, and H. Wei. Routing agents in wireless networks. Technical report, Department of Computer Science and Engineering, Southern Methodist University, January 1996.

[3] G. Cho and L. Marshall. An efficient location and routing scheme for mobile computing environments. *IEEE Journal on Selected Areas in Communications*, 13(5):868–879, June 1995.

[4] J. Ioannidis, D. Duchamp, and G. Maguire Jr. IP-based protocols for mobile internetworking. In *Proceedings of ACM SIGCOMM'91*, pages 235–245, September 1991.

[5] J. Ioannidis and G. Maguire Jr. The design and implementation of a mobile internetworking architecture. In *Proceedings of 1993 Winter USENIX*, pages 491–502, January 1993.

[6] D. Johnson. Mobile host internetworking using IP loose source routing. Technical Report CMU-CS-93-128, School of Computer Science, Carnegie Mellon University, February 1993.

[7] D. Johnson. Scalable and robust internetwork routing for mobile hosts. In *IEEE International Conference on Distributed Computing Systems*, pages 2–11, June 1994.

[8] J. McQuillan, I. Richer, and E. Rosen. The new routing algorithm for the ARPANET. *IEEE Transactions on Communications*, COM-28(5), May 1980.

[9] J. Moy. *OSPF Version 2.* Network Working Group, July 1991. RFC 1247.

[10] A. Myles, D. Johnson, and C. Perkins. A mobile host protocol supporting route optimization and authentication. *IEEE Journal on Selected Areas in Communications*, 13(5):839–849, June 1995.

[11] C. Perkins. Providing continuous network access to mobile hosts using TCP/IP. *Computer Networks and ISDN Systems*, 26:357–369, 1993.

[12] C. Perkins. *IP Mobility Support.* Network Working Group, October 1996. RFC 2002.

[13] Y. Rekhter and T. Li. *A Border Gateway Protocol 4 (BGP-4).* Network Working Group, March 1995. RFC 1771.

[14] F. Teraoka, K. Claffy, and M. Tokoro. Design, implementation and evaluation of virtual internet protocol. In *Proceedings of the 12th International Conference on Distributed Computing Systems*, pages 170–177. IEEE, 1992.

[15] K. Varadhan, S. Hares, and Y. Rekhter. *BGP4/IDRP for IP — OSPF Interaction.* Network Working Group, December 1994. RFC 1745.