# A First Performance Analysis of the Tree Morphing Approach to IPv6 Source Mobility in Source Specific Multicast Routing

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## Abstract

*Source Specific Multicast (SSM) promises a wider dissemination of group distribution services than Any Source Multicast, as it relies on simpler routing strategies with reduced demands on the infrastructure. However, SSM is designed for á priori known and changeless addresses of multicast sources and thus withstands any easy extension to mobility. Up until now only few approaches arose from the Internet research community, leaving SSM source mobility as a major open problem. This paper introduces a straightforward extension to multicast routing for transforming (morphing) source specific delivery trees into optimal trees rooted at a relocated source. All packet forwarding is done free of tunneling. Multicast service disruption and signaling overhead for the algorithms remain close to minimal. Furtheron we evaluate the proposed scheme using both, analytical estimates and stochastic simulations based on a variety of real-world Internet topology data. Detailed comparisons are drawn to bi-directional tunneling, as well as to proposals on concurrent distribution trees.*

**Keywords:** Routing Protocols, Mobile IPv6 Multicast, Source Specific Multicast, Multicast Mobility Management

## 1. Introduction

Mobility today must be seen as one of the major driving forces for multimedia data transmission. Cellular phones and portable paddles are expected to carry individual Internet addresses soon. These will be available from IPv6 address space, as is seamless mobility support from the recently released MIPv6 [10]. It is the vision that "IPv6 will be pervasive and prevalent across all digital device communications and augurs well for mobility and wireless access on the Internet" [12]. IP multicasting will be of particular importance to mobile environments, where users commonly share frequency bands of limited capacities.

Intricate multicast routing procedures, though, are not easily extensible to comply with mobility requirements. Any client subscribed to a group while in motion, requires delivery branches to pursue its new location; any mobile source requests the entire delivery tree to adapt to its changing positions. Significant effort has been already invested in protocol designs for mobile multicast receivers. Only limited work has been dedicated to multicast source mobility, which poses the more delicate problem [17, 19].

Source Specific Multicast (SSM) [2, 8], still in its design process, is considered a promising improvement of group distribution techniques. In contrast to Any Source Multicast (ASM) [4], optimal $(S, G)$ multicast source trees are constructed immediately from $(S, G)$ subscriptions at the client side, without utilizing network flooding or RendezVous Points. Source addresses are to be acquired by out of band channels such as SDR or a Web page. As a consequence, routing simplifies significantly, but invalidates with source addresses changing under mobility. Up until now SSM source mobility remains as an unsolved problem.

Source mobility presents a severe problem for multicast packet distribution. Even though multicast routing itself supports dynamic reconfiguration, as members may join and leave ongoing group communication over time, multicast group membership management and routing procedures are intricate and too slow to function smoothly for mobile users. In addition multicast imposes a special focus on source addresses. Applications commonly identify contributing streams through source addresses, which must not change during sessions, and routing paths in most protocols are chosen from destination to source.

Addresses in Internet mobility carry the dual meaning of logical *and* topological identifiers. While MIPv6 operates dual addresses transparently at end points, SSM routing needs to account for logical subscription *and* topological

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forwarding. Source specific group membership is identified via the logical ID of the sender, typically given by its Home Address (HoA); shortest path delivery trees are erected according to topological information as encoded in the current Care-of Address (CoA) of the Mobile Source. From this observation it can be concluded that any mobility transparent solution to SSM requires these dual information at intermediate routers and is forced to extend forwarding operations to process dual addressing.

In the present paper we start from this observation and present an approach to SSM routing, which adapts to source mobility. Operating on extended router states, our tree morphing algorithm first extends a given multicast distribution tree to include any new source location. It then transforms the extended tree to a new shortest path tree, thereby reusing all possible previously established branches. This scheme operates fast, without any tunneling and does not cause additional packet loss.

This paper is organized as follows: In section 2 we review the basic problems of SSM source mobility and related work. Section 3 introduces our new approach and defines the underlying routing algorithms. In section 4 we present the evaluation, analytical estimates and simulations of the proposed scheme. Finally section 5 is dedicated to conclusions and an outlook.

## 2. The Mobile Multicast Source Problem and Related Work

### 2.1. Problem Statement

Any next generation Internet support for multicast source mobility management is required to operate transparently wrt. the socket layer. Specific protocol operations or extensions are thus bound to a multicast aware MIPv6 stack and the Internet routing layer. Recalling the address duality problem, modified multicast routing protocols must be foreseen, as routing at the occurrence of source movement is required to transform any $(S, G)$ state into $(S', G)$, while listeners continue to receive multicast data streams. Hence any simple mobility solution such as the remote subscription approach of MIPv6 [10] loses its receivers and will no longer function in our context.

With SSM an additional address problem needs consideration: A multicast listener, willing to subscribe to an $(S, G)$ state, needs to account for the current location of the mobile source. Concurrently a general intricacy derives from the principle decoupling of multicast source and receivers: Any multicast source submits data to a group of unknown receivers and thus operates without feedback channel. Address updates on handovers of an SSM source have to proceed without means of the mobile source to inquire on properties of the delivery tree or the receivers.

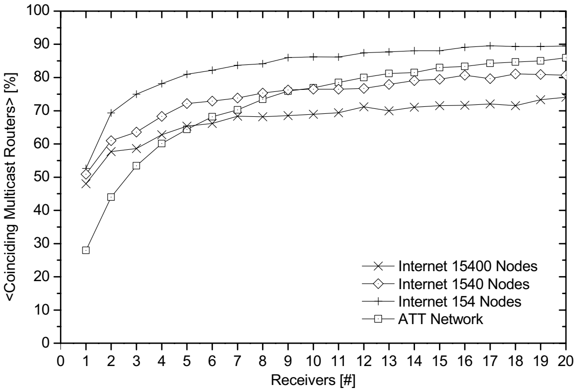

Figure 1. Relative router coincidence between subsequent multicast distribution trees for mobile senders and 'step size' 5.

All of the above severely add complexity to a robust multicast mobility solution, which should converge to optimal routes and, for the sake of efficiency, should avoid data encapsulation. Bearing in mind characteristic applications, i.e. multimedia distribution, handover delays are to be considered critical. The distance of subsequent points of attachment, the 'step size' of the mobile, may serve as an appropriate measure of complexity.

It is worth noting here that source specific shortest path trees subsequently generated from mobility steps are highly correlated: They most likely branch to the identical receivers and are rooted a step size apart. Figure 1 visualises the relative change of distribution trees as a function of receiver multiplicity for a medium step size of 5. It is interesting to note that even in large networks 75 to 80 % of multicast tree routers remain fixed under a mobility step. For details of the simulation we refer to section 3.

Finally, Source Specific Multicast has been designed as a light-weight approach to group communication. In adding mobility management, it is desirable to preserve the principal leanness of SSM by minimizing additional signaling overheads.

### 2.2. Related Work

Two principal approaches to SSM source mobility are presently around.

**Bi-directional Tunneling:** The MIPv6 standard proposes bi-directional tunneling through the home agent as a minimal multicast support for mobile senders and listeners. In this approach the mobile multicast source (MS) always uses its Home Address (HoA) for multicast operations. Since home agents remain fixed, mobility is completely hidden from multicast routing at the price of triangular paths and extensive encapsulation. Though robust and simple, it is well known that bi-directional tunneling may lead to overheads and delays from triangular routing unsuitable for real–time applications.

**Inter–Tree Handovers:** Several authors propose to construct a completely new distribution tree after the movement of a mobile source. These schemes have to rely on client notification for initiating new trees. At the same time they need to preserve address transparency to the client.

To account for the latter, Thaler [24] proposes to employ binding caches and to obtain source address transparency analogous to MIPv6 unicast communication. Initial session announcements and changes of source addresses are to be distributed periodically to clients via an additional multicast tree based at the home agent. Source–tree handovers are then activated on listener requests. In this proposed protocol data reception subsequent to handovers will be interrupted for the period of address announcement and tree reconstruction. It remains far too slow to be considered seamless. Overheads from the construction and maintenance of several trees are significant.

Jelger and Noel [9] suggest handover improvements by employing anchor points within the source network, supporting a continuous data reception during client–initiated handovers. Similar proxy schemes are known from improved unicast [23] or ASM [21] mobility. Receiver oriented tree construction in SSM remains unsynchronized with source handovers and thus will lead to an unforeseeable temporal progress. The authors are thus leaving the source in case of its rapid movement with an unlimited number of 'historic' delivery trees to be fed simultaneously.

Somewhat similar concepts have been presented in the MNet approach [22]. Multicast data is received by and redistributed through stationary multicast servers. Listeners may be triggered to inter–server handovers by ASM service announcement via SAP.

Even though it has not been applied to SSM, an additional group of work is of relevance to this paper.

**Tree Modification Schemes:** Very little attention has been given to procedures, which modify existing distribution trees to continuously serve for data transmission of mobile sources. In the case of DVMRP routing, Chang and Yen [3] propose an algorithm to extend the root of a given delivery tree to incorporate a new source location in ASM. To fix DVMRP forwarding states and heal RPF–check failures, the authors rely on a complex additional signaling protocol.

Focusing on interdomain mobile multicast routing in PIM-SM [5], the authors in [18] propose a tunnel–based backbone distribution of packets between newly introduced "Mobility-aware Rendezvous Points" (MRPs). These MRPs operate on extended multicast routing tables, which simultaneously hold HoA and CoA. This solution accounts for the ASM interdomain source activation problem [17].

Finally O'Neill [16] suggests a scheme to overcome reverse path forwarding (RPF) check failures originating from multicast source address changes, by introducing an extended routing information, which accompanies data in a Hop-by-Hop option header.

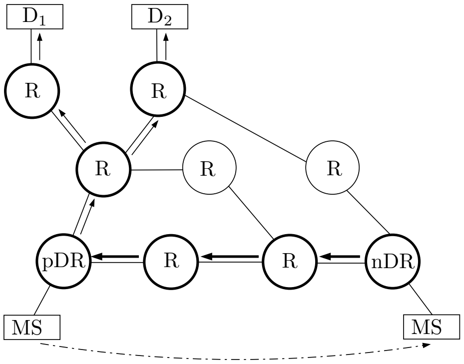

Figure 2. Elongation of the Tree Root

In the following section we will introduce an approach to the SSM mobile source problem, which falls in this last category of tree modifications.

## 3. Tree Morphing: An Algorithm to Source Mobility

### 3.1. General Idea

In the present section we will give a first overview of the new concept of multicast routing, adaptive to source mobility. A mobile multicast source (MS) away from home will transmit *unencapsulated* data to a group using its HoA on the application layer and its current CoA on the Internet layer, just as unicast packets are transmitted by MIPv6. In extension to unicast routing, though, the entire Internet layer, i.e. routers included, will be aware of the permanent HoA. Maintaining address pairs in router states like in binding caches will enable all nodes to simultaneously identify $(HoA, G)$–based group membership and $(CoA, G)$–based tree topology.

When moving to a new point of attachment, the MS will alter its address from previous CoA (pCoA) to new CoA (nCoA) and eventually change from its previous Designated multicast Router (pDR) to a next Designated Router (nDR). Subsequent to handover it will immediately continue to deliver data along an extension of its previous source tree. Delivery is done by elongating the root of the previous tree from pDR to nDR (s. fig. 2). All routers along the path, located at root elongation or previous delivery tree, thereby will learn MS's new CoA and implement appropriate forwarding states.

Routers on this extended tree will use RPF checks to discover potential short cuts. Registering nCoA as source ad-

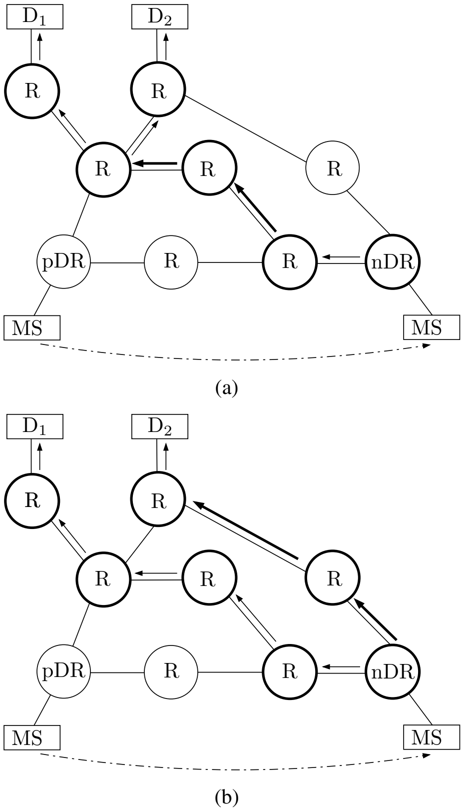

**Figure 3. Morphing States**

dress, those routers, which receive the state update via the topologically incorrect interface, will submit a join in the direction of a new shortest path tree and prune the old tree membership, as soon as data arrives. All other routers will re-use those parts of the previous delivery tree, which coincide with the new shortest path tree. Only branches of the new shortest path tree, which have not previously been established, need to be constructed. In this way the previous shortest path tree will be morphed into a next shortest path tree as shown in figure 3. This algorithm does not require data encapsulation at any stage.

## 3.2. Routing Requirements and Protocol Extensions

The tree morphing algorithm is not built upon a specific multicast routing protocol, but will require the following functional mechanisms, compliant with current protocols such as PIM-SM [5]:

- Outgoing router interfaces need to maintain $(S, G)$ states to denote their partition in the distribution tree. These states will be extended to include the Home Address identifier.
- Routers need the ability to explicitly *join* an $(S, G)$ state.
- Routers need the ability to explicitly *prune* an $(S, G)$ state. Alternatively, but with lower efficiency, routing states may time out.
- Finally, the computation of standard *Reverse Path Forwarding (RPF)* check is used.

As a first principal extension, all router states describing delivery trees for mobile sources need extension to include both, the transient CoA and the permanent HoA. They will be further denoted by $(S, G, HoA)$. These augmented states account for the address duality problem discussed in section 1 and will serve for identification of states during forwarding and updates.

Further mobility extensions to existing SSM routing protocols required by our algorithm are quite limited. Based on the standard functions mentioned above, protocols need to interpret a Hop-by-Hop multicast mobility option header as signaling. Routers then are required to process two algorithmic extensions described in section 3.4, the STATE INJECTION ALGORITHM and the EXTENDED FORWARDING ALGORITHM.

The details of signaling, MS and routing operations under mobility will be described in the following sections.

## 3.3. Mobile Source Handover Initiation and Signaling

We consider a multicast sender operating the mobility protocol MIPv6 [10], or accelerating schemes s.a. Fast MIPv6 [11] or Hierarchical MIPv6 [23], see [20] for multicast details. Prior to handover the MS is assumed to submit data to an intact source specific delivery tree, which need not necessarily be optimal. Data packets carry MS's current CoA as source address in concordance with $(CoA, G, HoA)$ states of the source tree. A mobility destination option header is included with data to signal the HoA to receiver applications. A multicast binding cache at the receiver site preserves the CoA : HoA correspondence.

The MS eventually may perform an instantaneous handover and fulfill MIPv6 reconfiguration. As soon as reassociated, the MS may immediately return to transmit unencapsulated data to the multicast group, using its topological correct nCoA as source address. To inform the routing infrastructure about its new location, it adds a state update message in a Hop-by-Hop option header to the first data packet(s) and uses source routing through the previous designated router pDR. This state update message will contain previous $(pCoA, G, HoA)$ and next $(nCoA, G, HoA)$ routing states, a sequence identifier and may include a security credential.

Following this update signaling, the MS continues to deliver multicast data as done prior to handover. It may proceed to a subsequent handover, as well.

## 3.4. Router Operations

A multicast routing infrastructure for SSM provides the capability to construct and deconstruct source specific delivery trees for stationary nodes. Our tree morphing algorithm will extend underlying routing protocols to include tree adaptability to mobile sources. We assume the abstract functions described in 3.2 to be present in the routing protocol and describe in detail the additional operations needed under source mobility now.

The tree morphing algorithm will proceed in three phases.

**Phase 1 – Tree Elongation:** As a Mobile Source moves, its designated multicast router may change and the root of the previous distribution tree may invalidate. To reconnect the established tree to a newly located root, a path from the nDR to the pDR is added according to unicast routing (s. fig. 2). This tree elongation is initiated by the MS's state update message (s. section 3.3), which is received by intermediate routers through the Hop-by-Hop option header on a unicast source route from nDR to pDR. On the reception of the update, any router will implement the new $(nCoA, G, HoA)$ state on its (unicast) forwarding interface. On arrival of the state update packet, pDR will – according to the source route – resend it destined for multicast group G, the group of the delivery tree rooted at pDR. At that instance a multicast branch of $(nCoA, G, HoA)$ states has been established from nDR to pDR.

**Phase 2 – Multicast State Injection and Forwarding:**[1] Once the state update packet has arrived at pDR, the previous root of the delivery tree, its Hop-by-Hop option header is processed along the previous tree. On each hop the new $(nCoA, G, HoA)$ state is implemented on the forwarding interfaces of the previous $(pCoA, G, HoA)$ – state tree. Previous states are kept only if the update packet was received on a topological incorrect interface. In detail this algorithm runs as follows:

```
STATE INJECTION ALGORITHM
  ▷ Upon receiving an $(nCoA,\ G,\ HoA)$
  ▷ state update for multicast group $G$
  for all $(\cdot, G, HoA)$ Forwarding Interfaces
      do if (RPF-CHECK($nCoA$) = TRUE)
          then REPLACE all $(\cdot,\ G,\ HoA)$-$states$
               by $(nCoA,\ G,\ HoA)$
          else ADD $(nCoA,\ G,\ HoA)$-$state$
               INIT TREE_OPTIMIZATION
```

After the update has been processed, the packet is passed along the newly implemented forwarding states. At this stage the delivery tree need not be optimal and packets may fail at standard RPF check (wrt. source address nCoA). To prevent discarding, incoming packets need to be accepted from any interface, which is a topological member of the current or a previous distribution tree of $(\cdot, G, HoA)$ state. Therefore an extended forwarding, which accounts for all source address states $(\cdot, G, HoA)$, has to be applied until local tree optimization has completed. Packets thereby will be forwarded along an $(\cdot CoA, G, HoA)$ tree, provided they arrived at the topologically correct interface for this $\cdot CoA$. A tree will be locally optimal, as soon as packets arrive at the topological correct interface. The details of this extended forwarding algorithm read:

```
EXTENDED FORWARDING ALGORITHM
  ▷ Upon arrival of packet with source address nCoA and
  ▷ in the presence of multiple $(*CoA,\ G,\ HoA)$-$states$
  for each $(\cdot CoA, G, HoA)$ Forwarding Interfaces
      do if (RPF-CHECK($nCoA$) = TRUE)
          then FORWARD_PACKET_ON_INTERFACE
               REMOVE $(*,\ G,\ HoA)$-$states$
               except $(nCoA,\ G,\ HoA)$
          else if (RPF-CHECK($\cdot CoA$) = TRUE)
               then FORWARD_PACKET_ON_INTERFACE
               else DISCARD_PACKET
```

In applying this forwarding algorithm, the delivery tree thus will not only transport intermediate detouring packets, but will continuously degenerate branches dispensable due to optimization incidences. As soon as $(\cdot, G, HoA)$ forwarding states have reduced to singular entries, the router operations continue as defined by its standard multicast routing protocol without mobility extension.

Finally state update packets will arrive at the receivers of the $(\cdot, G, HoA)$ SSM group. The mobile IPv6 stack capable of multicast tree morphing will interpret the Hop-by-Hop option header as a binding update and alter its multicast binding cache entry. Thereafter the standard destination option header is processed and data is transparently passed as $(HoA, G)$ to the transport layer.

**Phase 3 – Tree Optimization:** As a result of source movement with successive tree elongation, but also from any intermediate morphing state, the delivery tree may cease to be optimal. Any router will observe suboptimal routes from packets arriving at a topological incorrect interface (w.r.t. packet's source address). As part of the algorithm it will then dynamically attempt to join to an optimal shortest path tree. When receiving a multicast packet for group $(\cdot, G, HoA)$ with source address $nCoA$ at the wrong interface, a router will immediately submit a join to $(nCoA, G)$. The underlying SSM routing protocol

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[1] Further on we will denote "some state with group address $G$ and home address $HoA$" by $(\cdot, G, HoA)$, whereas $(*, G, HoA)$ stands for all such states.

will initiate the construction of a shortest path source specific branch. The router will learn about its completion by $(nCoA, G, HoA)$ traffic arriving at the correct interface and will then prune $(*, G, HoA)$ on all incoming interfaces corresponding to previous $CoA$ addresses.

Once an intermediate router learned about suboptimal routes, this algorithm will perform optimization as rapid as possible. The scheme is self-healing and robust, but will construct any possible short cut, even though not part of the final shortest path tree.

## 4. Evaluation & Simulation

To judge on the quality of the proposed scheme, we investigate the following aspects of significant relevance.

### 4.1. Handover Initiated Packet Loss and Delay

Regular MIPv6 handovers may in general lead to packet loss and delay, which can be minimized by accelerating protocols such as FMIPv6 [11] or HMIPv6 [23]. There will be no additional packet loss caused by the tree morphing multicast handover, since a Mobile Source is enabled to immediately transmit multicast data. The initial tree elongation may result in triangular routing according to the distance between $pDR$ and $nDR$. Subsequent tree optimization will monotonically reduce suboptimal paths.

It should be noted that state update messages injected subsequent to handover may immediately override router states from the previous distribution tree. This in principle may lead to dropping of delayed and overrun packets. However, taking into account that update packets are issued only after the delay of layer 2 and layer 3 handover and – after reaching the previous distribution tree through $pDR$ – are forwarded along the identical, possibly congested path and traffic class, only significant malfunctions of a network may possibly lead to packet overrun and the additional loss from that cause.

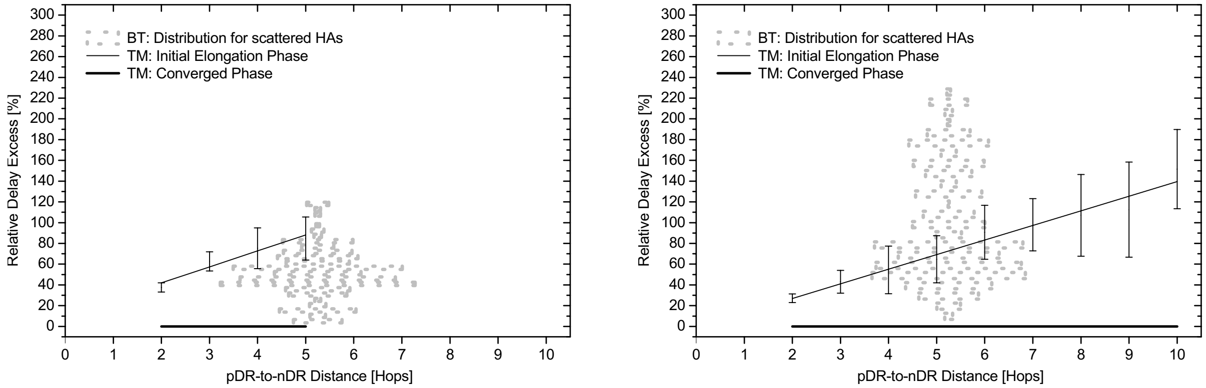
To judge on performance quality of the tree morphing (TM) scheme, we now analyze its delay effects within realistic Internet topologies. We performed a stochastic discrete event simulation based on the network simulator platform OMNeT++ 3.1 [25] and several real–world topologies of different dimensions. The selection of network data in our simulation must be considered critical, as key characteristics of multicast routing only make an impact in large networks, and as topological setup fixes a dominant part of the degrees of freedom in routing simulations.

We chose the ATT core network [7] as a large (154 nodes), densely meshed single provider example. For inter–provider data we extracted sub-samples of varying sizes from the "SCAN + Lucent" map [1, 6], the result of two extensive Internet mapping projects containing 284.805 network nodes connected by 449.246 links. Sub-sampling has been performed with the help of the network manipulator *nem*, employing the generation method "Map Sampling" [13, 14]. Sample sizes, 154, 1.540 and 15.400 nodes, vary by two orders of magnitude. The Boston Generator BRITE [15] has further been used for topology generation and format transformation.

The delay excess relative to optimal routes has been calculated as characteristic performance measure under the assumption of homogeneous link delays. Extreme values, i.e. maximal delays at initial elongation phase and minimal after convergence, were evaluated for tree morphing (TM) as functions of the distance from $pDR$ to $nDR$. In detail, designated routers within a given topology were randomly chosen edge routers (node degree = 1) according to their predefined distances. For each pair of edge routers at the mobile source a uniformly distributed set of 20 receivers was established and delay values were taken from average reception time. Sampling of source positions was repeated 20 times for each parameter set in order to better explore the large phase space. Comparisons are drawn with bi-directional tunneling (BT), which does not depend on designated router distances, but on HA position. The delay excess in BT as function of HA position does not converge to a characteristic value, but rather admits a broad distribution. The latter has been derived from scattering HA positions uniformly from core routers (node degree $> 1$) within the sample networks. It should be noted that these simulations concern delays for all three distribution trees in presence and thus qualitatively cover the solutions discussed in section 2. Aside from additional signaling overhead, BT reflects the delays of [24], TM those of [9].

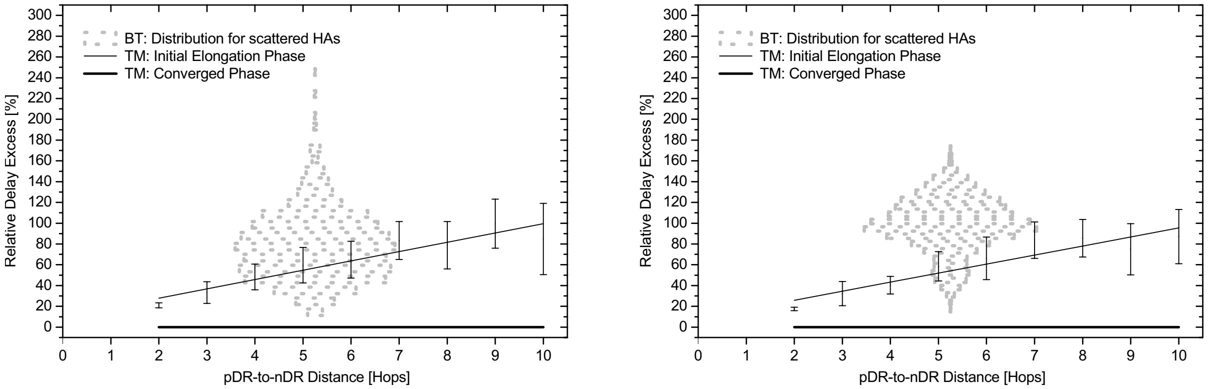
The results of our simulations are displayed in figure 4. $pDR$ to $nDR$ distances were chosen between 2 and 10, except for the ATT network, which exhibits a maximal edge router separation of 5. Error bars indicate the standard deviation of initial TM delay excess, as calculated from events differing in location of the mobile source. Plotted lines indicate the linear regression curves derived from this result set. Delay excess distributions for scattered HAs in BT are laid underneath TM curves in grey dots.

It can be observed that initially maximal delays of the tree morphing scheme tend to remain below the average of permanent BT packet retardation. Convergence of the TM then will lead to (relatively) undelayed packet delivery, which is never met in BT. Little dependence on network size becomes visible for TM — relative delays more strongly change with topologic characteristics. In a densely meshed provider network such as the ATT core, packet transitions are rapid and therefore initial delays from tree elongation account more dominantly for our relative measure. In the contrary it is interesting to note that delays from BT ad-



(a) ATT Core Network

(b) Internet 154 Nodes



(c) Internet 1.540 Nodes

(d) Internet 15.400 Nodes

**Figure 4. Excess Delay of Optimal Routes: Comparison of BT and TM, Initial and Converged Phase, for Different Network Topologies**

mit a systematic dependence on network size: BT average delay excess increases from 45 % in the small ATT network to about 120 % in the 15.400 node multiprovider Internet. From these observations it can be concluded that bi-directional tunneling attains appropriate performance for small communities within a densely meshed core network, but becomes infeasible in large inter-provider domains. The tree morphing even in its initially weakest phase exhibits fairly uniform performance, no matter how large the underlying network is.

## 4.2. Robustness and Protocol Convergence

The tree morphing scheme is robust in the sense that it transforms any intact, not necessarily optimal distribution tree into a new SSM shortest path tree rooted at the new source location. This can be easily observed from $(*, G, HoA)$–states being only completely removed by the underlying multicast routing protocol, whose correctness is assumed. All intermediate router states conduct loop–free packet forwarding, as packets are sent down a coherent concatenation of shortest path trees. At any stage this resulting distribution tree does not attain an overall loop, but connects all receivers with the current source. Even though tree branches may intersect, any packet forwarding decision is based on only one underlying branch, which is identified by its corresponding RPF check. The algorithm is self–healing.

Robustness of signaling in our scheme is equivalent to the degree of reliability in packet distribution. As there is no acknowledgement in multicast and as strongly asymmetric shortcuts may lead to packet overrun, the Hop-by-Hop state update message should be piggybacked not only with the first, but rather with a first sequence of data packets. In QoS domains update packets should be classified with lowest drop precedence as not to be discarded by routers.

The tree morphing algorithm is robust under rapid movement. This can be concluded from observing that elongation at the tree root will equally function in multiple steps, while tree optimization will work on any distribution tree. Routing convergence under rapid MS's movement is assured even in the case of ping–pong mobility, as long as the tree elongation step can complete, i.e. the frequency of motion remains above the packet traveling distance between $pDR$ and $nDR$. The latter assumption must be considered weak.

The convergence of the routing algorithms attains two measures, one for the time to reach optimal packet forwarding and the other for the final convergence to an optimal shortest path source tree.

**Observation 1** *For any receiver $D_i$ the Tree Morphing Protocol has converged to optimal packet forwarding, iff multicast packets submitted by the mobile source are forwarded to $D_i$ along the shortest (reverse unicast) path from $D_i$ to MS.*

**Observation 2** *For any receiver $D_i$ and group $(nCoA, G, HoA)$ the Tree Morphing Protocol has converged to minimal shortest path tree, iff all router states $(\cdot, G, HoA)$ forwarding towards $D_i$ are member of the shortest path $(nCoA, G, HoA)$ source tree.*

Consequently the total time to convergence $T_{conv}$ decomposes into the time to optimal packet forwarding $F_{conv}$ and the additional time $M_{conv}$ needed for reshaping the tree to the minimal, i.e.

$$T_{conv} = F_{conv} + M_{conv}.$$

To evaluate the rate of convergence to optimal packet forwarding after source handover, consider any receiver $D_i$ and the router $X_i$ of intersection between the previous and the next shortest path delivery tree towards $D_i$. If $X_i = pDR$, i.e. tree elongation alone has formed an optimal tree, forwarding is always optimal. Otherwise the time $F_{conv}^{(i)}$ to forwarding convergence will be bound by the successive signaling from the MS to $pDR$, following down the previous forwarding tree and returning to $nDR$ via the last initiation point of shortcut, which is given by the tree intersection $X_i$. This will be equivalent to the unicast forwarding time from $nDR$ via $pDR$ via $X_i$ back to $nDR$. Denoting by $dist_u^v$ the distance from $u$ to $v$, then

$$F_{conv}^{(i)} \leq dist_{nDR}^{pDR} + dist_{pDR}^{X_i} + dist_{X_i}^{nDR}. \qquad (1)$$

As all tree optimizations are performed in parallel, the total time to optimal forwarding convergence is given by

$$\begin{aligned} F_{conv} &= \max_i \{F_{conv}^{(i)}\} && (2) \\ &\leq dist_{nDR}^{pDR} + \max_i \{dist_{pDR}^{X_i} + dist_{X_i}^{nDR}\}. \end{aligned}$$

As an example consider $nDR$ and $pDR$ to be located in adjacent domains connected by a single peering point $P$. Aside from local branches the only tree intersection point will be $P$, which simultaneous lies on the route between $pDR$ and $nDR$. Thus $F_{conv} = dist_{nDR}^{pDR} + dist_{pDR}^{P}$ and Router signaling attains a communication overhead close to the possible minimum $dist_{nDR}^{pDR}$ between the two multicast domains.

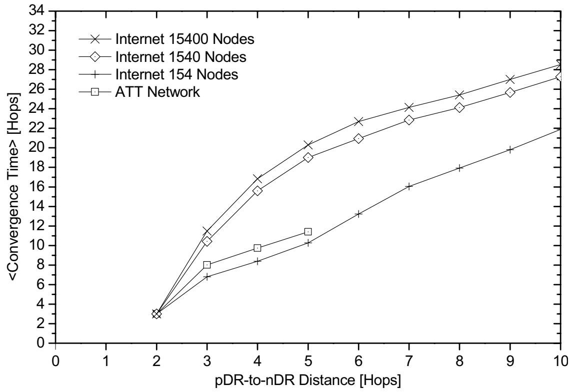


**Figure 5. Mean Convergence Time to Optimal Packet Forwarding for the Tree Morphing as Function of DR Distance**

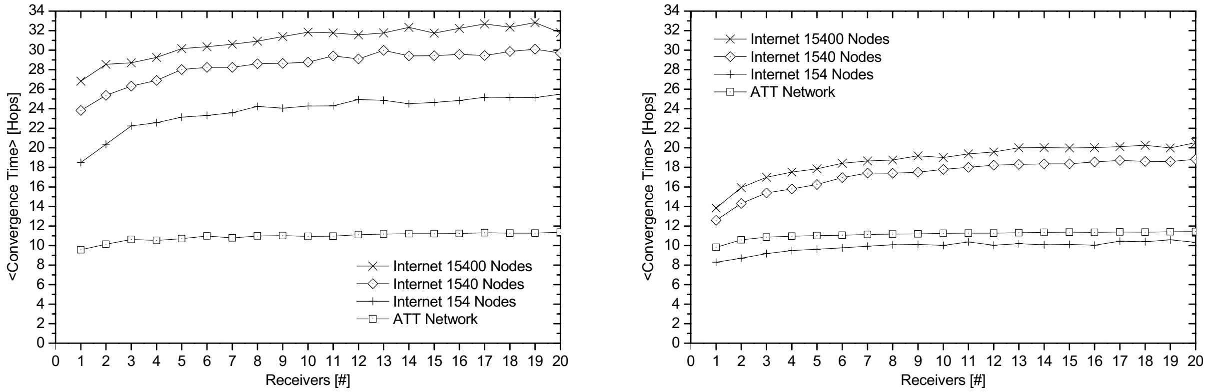
Subsequent to optimal packet forwarding, distribution trees are reduced to minimal shortest path trees. For any receiver $D_i$ the router $X_i$ of intersection between the previous and the next shortest path delivery tree towards $D_i$ will initiate prunes on the (possibly already degenerate) former distribution branches, as soon as optimally forwarded packets arrive. Signaling thereby follows a path inverse to state injection from $X_i$ to $pDR$. Hence the convergence time $M_{conv}^i$ to tree minimization after optimal forwarding does never exceed $F_{conv}^{(i)}$. As in general all possible shortcuts are used and the previous delivery tree may have been partially deconstructed, the inequalities

$$M_{conv} \leq F_{conv} \quad \text{and} \quad T_{conv} \leq 2\ F_{conv} \qquad (3)$$

rigorously hold.

In our above example $M_{conv} = dist_{P}^{pDR}$, whence the total convergence to final tree geometry $T_{conv} = dist_{nDR}^{pDR} + 2\ dist_{pDR}^{P}$ will be in the order of one roundtrip time between $pDR$ and $nDR$.

To treat more complex scenarios we performed stochastic simulations of the tree morphing protocol signaling within the OMNeT++ platform and Internet topology data as described in section 4.1. Mean values of $F_{conv}$, the convergence of the routing protocol to optimal packet forwarding, have been calculated for samples as obtained in the previous section. Convergence time is evaluated pathwise in units of router hops under the assumption of homogeneous link delays. Comparison is drawn to an expedited, idealized HA–Handover scheme derived from [24]: As the work of Thaler has not been detailed out, we disregard any



(a) Expedited HA Scheme

(b) Tree Morphing at pDR-to-nDR distance 5

**Figure 6. Mean Convergence Time to Optimal Packet Forwarding: Comparison of an Idealized HA–based Handover Scheme and TM as Functions of Receiver Multiplicity**

messaging overhead to be defined therein and assume that the mobile node subsequent to handover will immediately signal its new CoA to its receivers down its permanent HA–based tree. On the reception of updates multicast listeners are then expected to immediately join the tree towards the new source location, such that optimal packet flow is reached with shortest path tree's completion. Following this idealized setting we calculate a lower bound for the time to optimal packet forwarding of the handover procedure proposed in [24].

The mean convergence time for the tree morphing as a function of $pDR$ to $nDR$ distance is displayed in figure 5. A sharp minimum can be observed for small designated router distances, where the tree morphing protocol admits its best performance. Curves for all topologies coincide in their minimum at distance two, which is due to the geometric property that only the tree intersecting router connects the two DRs, independent of network topology.

Convergence for close distances of designated routers is attained after only a few router hops and mobility effects then remain almost invisible. Asymptotically its mean dependence on designated router distance as derived from the slopes of curves nicely approaches the roundtrip time between those DRs. Facing equation 2 it can be concluded that even in large networks and DRs far apart, routers of intersection between the previous and next multicast tree remain within the region of source attachments. This result corresponds to the á priori observation discussed in section 2 that multicast distribution trees obtained from subsequent mobility steps are not uncorrelated, but are likely to significantly overlap.

Figure 6 compares the convergence times of the tree morphing protocol at a designated router distance of 5 with the corresponding results of the idealized HA scheme derived from [24] as functions of receiver multiplicities. In general, both schemes nicely reproduce their multicast nature by showing very little dependence on receiver numbers. For TM this approves the previously assumed parallel processing of shortcuts. While results for the single provider ATT network closely coincide, TM significantly outperforms the HA scheme for multiprovider Internet topologies of all sizes. This basically reflects its ability to reuse increasing parts of the wider branched trees, whereas the inter–tree handover approach always requires the recreation of all routing states.

## 5. Conclusions and Outlook

In this paper we presented an approach to solve the mobility problem in SSM routing. This novel scheme of morphing a previous distribution tree into a new shortest path tree operates based on common multicast routing protocols with simple algorithmic extensions. After a handover it allows for immediate data transmission and strictly avoids data encapsulation.

Characteristic aspects of this tree morphing algorithm subsequently were analyzed, donating special focus on delay performance and protocol convergence. A rigorous upper bound for convergence was derived from a coincidence measure of the previous and the next distribution tree. All procedures could be shown to be robust and self–healing. Forwarding delays and convergence subsequent to handover have been calculated by stochastic simulations using real–world Internet topologies. It was found that maximal delays of the tree morphing scheme on average remain below packet retardation in bi-directional tunneling. Furthermore delays in our algorithm could be shown to perform independently of network size, while bi-directional tunneling performance degrades with network scaling. Protocol convergence times remained systematically below corresponding values of competitive approaches and were found negligible for small mobility 'step sizes'.

In future work we will quantify and compare further characteristic measures of the scheme. A formulation of a corresponding security layer will be on schedule, as well.

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