Towards Seamless Source Mobility in SSM — Design and Evaluation of the Tree Morphing Protocol

Olaf Christ, Thomas C. Schmidt*

Dept. Informatik, HAW Hamburg,
Berliner Tor 7, D–20099 Hamburg, Germany
E-mail: olaf@solutionworks.de, t.schmidt@ieee.org
*Corresponding author

Matthias Wählisch†

link-lab
Hönower Str. 35, D-10318 Berlin, Germany
E-mail: waehlisch@ieee.org
†Also with Freie Universität Berlin and HAW Hamburg

Abstract: Multimedia networking in the near future is expected to be dominated by group applications such as IPTV, MMORPGs, and video conferencing. Hand in hand with new service offers, the deployment of multicast at the network layer started to disseminate. Currently infotainment is gradually expanding into the mobile world, but a standard design of mobile multicast is still awaited.
In this paper we present a design and discuss an extensive evaluation of the Tree Morphing Protocol that performs an adaptive tree management to support seamless handovers for mobile SSM sources. Based on a full protocol implementation on a network simulator platform, we extensively explore the protocol performance. By employing artificial networks to cover fundamental topological constellations, as well as real-world network topologies, we analyze the handover behavior conceptually and in realistic scenarios. Strengths and weaknesses of the routing scheme are identified, leading to a discussion on future improvements.

Keywords: Mobile source specific multicast, route optimization, Mobile IPv6, protocol performance, verification, simulation

Reference to this paper should be made as follows: Christ, O., Schmidt, T.C., and Wählisch, M. (2008) 'Towards Seamless Source Mobility in SSM - Design and Evaluation of the Tree Morphing Protocol', Int. J. Internet Protocol Technology (IJIPT), Vol. 3, Nos. 4, pp.205-215.

Biographical Notes: Olaf Christ graduated from Hamburg University of Applied Sciences (HAW) recently with his master thesis about the analysis, simulation and verification of the Tree Morphing Protocol. His fields of interest lie in computer networking and real-time operating systems, where he acquired several years of experiences in research and industry work. Olaf received several awards for his outstanding work

completed in his master project.

Thomas C. Schmidt is professor of Computer Networks & Internet Technologies at Hamburg University of Applied Sciences (HAW) and leads the research group on Interacting Multimedia Systems (IMS) there. Prior to moving to Hamburg, he headed the computer centre of FHTW Berlin for many years, and continued work with FHTW as an independent project manager later. He studied mathematics and physics at Freie Universität Berlin and University of Maryland. He has continuously conducted numerous national and international projects. His current interests lie in next generation Internet (IPv6), mobile multicast and multimedia networking, as well as XML-based hypermedia information processing. He serves as co-editor and technical expert in many occasions and is actively involved in the work of IETF.

Matthias Wählisch is the co-founder of link-lab, a start-up company in the field of next generation networking. He is also with the IMS research team at HAW Hamburg, after he had been with the networking group of the computer centre of FHTW Berlin, and with Freie Universität Berlin, Institut für Informatik, where he studied computer science and contemporary German literature. His major fields of interest lie in the design and analysis of networking protocols, where he looks back on ten years of professional experience in project work and publication.

1 Introduction

Networked multimedia applications such as voice and video (group) conferencing, large scale content distribution (e.g., IPTV) and massive multiplayer games (MMORPGs) are considered the key applications for the next generation ubiquitous Internet. The latter is expected to be truly mobile and to grant globally valid addresses to all of its members. Inexpensive, point-to-multipoint enabled technologies such as 802.16 or DVB-H/IPDC emerge on the subnetwork layer and facilitate large-scale group communication deployment. But unlike point-to-point mobility (Johnson et al., 2004) and despite of ten years of active research, mobile multicast protocol development is still in an early, premature state (Schmidt et al., 2008b).

This paper addresses the issue of mobile Source Specific Multicast routing on the network layer and the Tree Morphing protocol (TM) protocol proposal. Source Specific Multicast (SSM) by Holbrook and Cain (2006), just released as an initial standard, is considered a promising improvement of group distribution techniques. In contrast to Any Source Multicast (ASM) (Deering, 1989), 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, which a SIP (Rosenberg et al., 2002) session initiation in conferencing scenarios may facilitate (Schmidt and Wählisch, 2008).

We discuss session mobility in the context of real-time multicast. Conferencing parties request seamless real–time performance of a mobility aware group communication service, thereby attaining the simultaneous roles of mobile multicast listener and source. The Tree Morphing protocol (TM) introduced by Schmidt and Wählisch (2005, 2006), one of the few approaches to SSM source mobility management, proposed an algorithm to enable immediate, unencapsulated multicast data transmission subsequent to Mobile IPv6 handovers. After an extensive phase of protocol design, implementation and evaluation, we are now ready to present details on the Tree Morphing properties, as well measures of the protocol performance.

As will be shown in the remaining paper, the TM adheres to real-time compliant performance in various, realistic routing topologies, but admits several weaknesses, which give rise to future improvements. In this paper we first discuss the mobile multimedia group conferencing problem and related work in section 2. Section 3 presents a complete implementation and verification of the protocol at the packet level. A thorough evaluation of the Tree Morphing follows in section 4. Finally, section 5 is dedicated to a conclusive discussion and an outlook.

2 Mobile Source-Specific Multicast

2.1 Problem Statement

A mobile multicast sender will face the problem of enabling a continuous forwarding of data to its group of receivers, while it undergoes roaming and network layer handovers. Its mobility protocol should facilitate a seamless transmission service and at the same time preserve transparency with respect to network and address changes at the receiver side. Multicast listener applications are frequently source address aware. A mobile multicast source consequently must meet address transparency at two layers: To comply with RPF checks, it has to use an address within the IPv6 basic header's source field, which is in topological concordance with the employed multicast distribution tree. For application transparency, the logical node identifier, commonly the Home Address, must be presented as the packet source address to the transport layer at the receivers.

At the complementary side, network routing must comply with the sender movement without having network functionality compromised. It should realize native forwarding whenever possible to preserve its resources, but needs to ensure routing convergence even under a rapid movement of the sender. Mobility support for multicast sources at the network layer thus poses a significant challenge to the infrastructure. An SSM node submitting data to a group of receivers defines the root of a source specific shortest path tree (SPT), distributing data towards its receivers. Native forwarding along source specific delivery trees will be bound to the source's topological network address due to reverse path forwarding (RPF) checks. A mobile multicast source moving to a new subnetwork is only able to either inject data into a previously established delivery tree, which may be a rendezvous point based shared tree, or to (re-)initiate the construction of a multicast distribution tree compliant to its new location. In the latter case, the mobile sender will have to proceed without controlling the new tree development, as it operates decoupled from its receivers.

Finally, security and admission control issues arise with new care-of source addresses being introduced to SSM channels at handovers. Multicast receivers that evaluate binding caches for source identification are subject to impersonation and a theft of service, unless binding updates of a mobile source can be authenticated, as comprehensively discussed by Kellil et al. (2005). The SSM design permits trust in equivalence to the correctness of unicast routing tables, which must be preserved throughout the mobile regime.

2.2 Related Work

Three principal approaches to SSM source mobility are presently around.

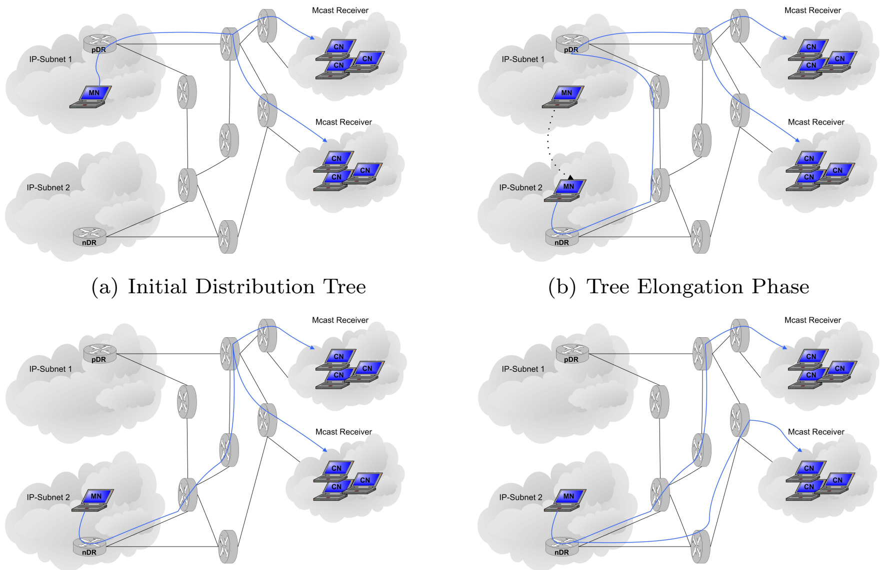
Statically Rooted Distribution Trees: The MIPv6 standard proposes bi-directional tunneling through the home agent as a minimal multicast support for mobile senders and listeners. In this approach, the mobile multicast source (MS) always uses its Home Address (HoA) for multicast operations. Since home agents remain fixed, mobility is completely hidden from multicast routing at the price of triangular paths and extensive encapsulation.

Following a shared tree approach, Romdhani et al. (2006) propose to employ Rendezvous Points of PIM-SM (Fenner et al., 2006) as mobility anchors. Mobile senders tunnel their data to these "Mobility-aware Rendezvous Points" (MRPs), whence in restriction to a single domain this scheme is equivalent to the bi-directional tunneling. Focusing on interdomain mobile multicast, the authors design a tunnel– or SSM–based backbone distribution of packets between MRPs.

Reconstruction of Distribution Trees: 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 router state establishment. At the same time they need to preserve address transparency to the client. To account for the latter, Thaler (2001) 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 control tree based at the home agent. Source–tree handovers are then activated on listener requests. Jelger and Noel (2002) suggest handover improvements by employing anchor points within the source network, supporting a continuous data reception during client–initiated handovers.

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 ASM case of DVMRP routing, Chang and Yen (2004) propose an algorithm to extend the root of a given delivery tree to incorporate a new source location. O'Neill (2002) suggests a scheme to overcome 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.

A routing protocol adaptive to SSM source mobility, the Tree Morphing as visualized in figure 1, has been introduced by Schmidt and Wählisch (2005, 2006). A mobile multicast source (MS) away from home will transmit unencapsulated data to a group, using its current care-of address (CoA) on the Internet layer, but HoA on the application layer, which is carried in extension headers like in MIPv6. In extension to unicast routing, though, the entire Internet layer, i.e. routers included, will be aware of the permanent HoA. Maintaining binding-cache-like address pairs in router states will enable all routers to simultaneously identify (HoA, G)–based group membership and (CoA, G)–based tree topology. When moving to a new



(a) Initial Distribution Tree (b) Tree Elongation Phase

(c) Intermediate Morphing Phase (d) Converged Distribution Tree

Figure 1 Tree Morphing States

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 using source routing from nDR to pDR. Delivery proceeds by elongating the root of the previous tree from pDR to nDR (s. fig. 1(b)). All routers along this path will learn the new CoA of MS and implement appropriate forwarding states.

Routers on this extended tree will use RPF checks to discover potential short cuts. Registering nCoA as source address, 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 at the correct interface. 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 showin in figure 1(c)

3 Tree Morphing Protocol Implementation

Mobility-adaptive tree management schemes attempt to facilitate seamless handovers by sustaining a continuous contact to the receivers, at the price of an increased complexity of router operations. Even though these protocols can take advantage of limited mobility-related changes in the shapes of multicast distribution trees that can be observed (Wählisch and Schmidt, 2007), a light-weight protocol design is vital to limit overheads inherited from the complexity of tree adaptation. In this section we will present an implementation of the tree morphing protocol that complies well with complexity constraints, its actual performance characteristics will be presented in the next section.

3.1 Objectives

The Tree Morphing Protocol requires a forwarding state update at the router infrastructure layer subsequent to any multicast source handover. In detail, the multicast distribution tree rooted at the pDR has to be transformed into a tree centered at nDR, as soon as Mobile IPv6 handover operations of the mobile source are completed. In order to implement this changes in tree topology, packets have to signal the update context given by (HoA, G) and the new multicast forwarding states $(nCoA, G)$. Immediately following a handover, these three IP addresses have to be transmitted to all routers of the previous and - if possible - new distribution tree.

Regular SSM packets will invalidate from source filters at the routing layer, when transmitted at a new point of attachment of the mobile source. It is therefore important that routing states are updated prior to packet forwarding. The state update information required resemble mobility binding updates as operated by MIPv6 at unicast end nodes[a]. Since an additional signaling would add undesired overhead, a major objective lies in re-using these binding update information carried with data packets immediately following the handover. By using this 'piggyback' mechanism, further undesired conditions, such as packet disordering, can be avoided. Even though payload packets can still arrive in an incorrect order, it should be guaranteed that the first packets contain the update instructions. The update thereby can be processed on arrival of any first packet. Additional control to improve reliability should be foreseen.

Additionally, the protocol operation should require minimal extensions to the existing mobility signaling in order to design a simple and standard compliant protocol. The following implementation of the Tree Morphing Protocol is therefore realized by combining existing protocol structures with only few, unavoidable extensions, i.e., a modified Hop-by-Hop option. Furthermore, special focus must be denoted to protocol security, as the state updates performed in the Internet infrastructure are susceptible to theft of identity and impersonation.

3.2 Protocol Design

A multicast source acquiring a new care-of source address needs to signal its state update to every router along the source-specific multicast distribution tree. The required information, group address, home address and care-of address, are already part of Binding Update messages sent by mobiles to correspondent end nodes subsequent to every handover. In order to enable visibility at routers of such transparent multicast mobility signaling, a Router Alert Option is inserted in a Hop-by-Hop Option Header (Partridge and Jackson, 1999). This option is used to instruct routers to further inspect packet headers, which is normally omitted

[a]Regarding the current state of knowledge (Schmidt et al., 2008b), a Binding Update can be foreseen to be part of all future solutions for multicast source mobility.

according to the IPv6 specification of Deering and Hinden (1998). By placing a specific alert in the Hop-by-Hop Option Header, further instructions are processed by every router along the paths of the packets. Corresponding header chains vary in different phases of the Tree Morphing Protocol and will be described in the following sections.

3.2.1 Protocol Security

State update packets initiate a multicast re-routing and require strong authentication of the sender. The proof of identity is equivalent to proving the HoA-ownership, and – according to the multicast paradigm – must proceed unidirectonally without feedback. To achieve this goal, the Tree Morphing takes advantage of the AuthoCast Protocol (Schmidt et al., 2008a), which itself is implemented as an extension of MIPv6 enhanced route optimization by Arkko et al. (2007) and relies on cryptographically generated addresses (CGAs) (Aura, 2005). AuthoCast exhibits cryptographically strong authentication of the state update signaling in an autonomously verifiable, unidirectional way.

3.2.2 Tree Elongation Phase

The mobile source performs loose source routing to implement extended states immediately after a handover. Figure 2 shows the packet format during this Tree Elongation phase. The update packet is sent to the previous Designated Router (pDR) by the MN, using it's currently valid CoA. Compliant with the extension header order in Deering and Hinden (1998), the following header has to be the Hop-by-Hop Option header containing a Router Alert Option. The following Destination Option header contains the Home Address Option Johnson et al. (2004), which signals the HoA to the receivers, succeeded by the MIPv6 Binding Update parameters. The CGA Parameter Option and the CGA Signature Option are specified in Arkko et al. (2007) and contain all necessary data for a CGA authentication. It should be remarked that multiple CGA Parameter Options can be stored sequentially in one Mobility Header. The last header consists in a Routing Header of a specifically defined type, e.g. 7. In contrast to MIPv6, the address field may only contain one valid multicast address, allowing for application specific source routing. It allows for source routed packets with final destination of a multicast group. Furthermore, by defining a new type, dedicated firewall rules can be applied for state update messages. Finally, the upper layer header including data is the last part of the message.

IPv6 Header	Hop-by-Hop Options Header	Dest. Options Header	Mobility Header			Routing Header	Upper Layer Header + Data
Src: CoA Dst: pDR	Router Alert Option	Home Address Option	Binding Update Message	CGA Param. Option	CGA Signature Option	Addr[0] = G	Data

Figure 2 IPv6 header sequence including the State Update Message during Tree Elongation Phase on Path from Next to Previous Designated Router

In rigorously reliable networks without packet loss, the state update message could be sent only once in the first packet subsequent to a multicast source handover. Since real networks are error-prone, error resilient mechanisms have to be used to inform the source of successfully injecting the new states in all the routers along the path of tree elongation. As the pDR is the end point of the source routing path and can deliver confirmations reasonably, it is chosen to send a Mobile IPv6 Binding Acknowledgement Message (see Johnson et al. (2004)) to the mobile node, once a new state update message has been received successfully. It thereby secures the transmission of state updates along the tree elongation path, since source routing is used to deliver packets from the mobile node to the pDR. Once the mobile node has received the confirmation message, it may include the state update message in further packets to ensure a desired degree of redundancy for state update distribution along the multicast tree.

3.2.3 On–Tree Multicast Transmission

After the source routing, further multicast transmission originates from the pDR and re-uses the delivery tree established prior to handover. The packets sent during regular multicast transmission (see figure 3) will be stripped of the Routing Header as soon as the source routing transition point pDR has been reached. This is achieved by copying the group address G from the Routing Header into the destination address field of the IPv6 header.

IPv6 Header	Hop-by-Hop Options Header	Dest. Options Header	Mobility Header			Upper Layer Header + Data
Src: CoA Dst: G	Router Alert Option	Home Address Option	Binding Update Message	CGA Param. Option	CGA Signature Option	Data

Figure 3 IPv6 header sequence including the State Update Message from Previous Designated Router to Multicast Group

3.3 Protocol Verification

In this section we report on the verification of the Tree Morphing protocol with the help of its formal description using the PROcess MEta LAnguage (PROMELA) by Holzmann (1991). The entities under consideration are multicast router interfaces that perform group management operations.

The finite state machine of such a downstream interface at a Tree Morphing router is derived of the PIM-SSM (Fenner et al., 2006) state machine and displayed in figure 4. The states No Info (NI), Join (J) and Prune Pending (PP) interact as in standard PIM-SSM. The Join state is augmented by a Tree Morphing (TM) state, which represents the router conditions during mobility management and prior to protocol convergence. On the reception of a state update packet, router may remain in J state, if the RPF check is successful (state override). Otherwise, a transition into the TM state follows. Its characteristic then lies in a state splitting initiated from the update messages, which in the event of rapid movement may be received multiple times prior to convergence. This is realized via a state counter and allows for a joined treatment of the correlated $(\cdot, HoA, G)$ stated within routers. An expiry timer (ET) is used to survey the soft states and restore the NI base-state.

Packets, communication channels and timer control have been implemented in PROMELA, as well as a random message generator, to assert that the protocol is deadlock- and livelook-free and admits liveness. The tool SPIN (Simple Promela INterpreter) (Holzmann, 1997) is used to validate the model. The verifier was compiled using full state space search for safety and liveness. Execution of the verifier confirmed that our protocol model is free of errors and there are no assertion

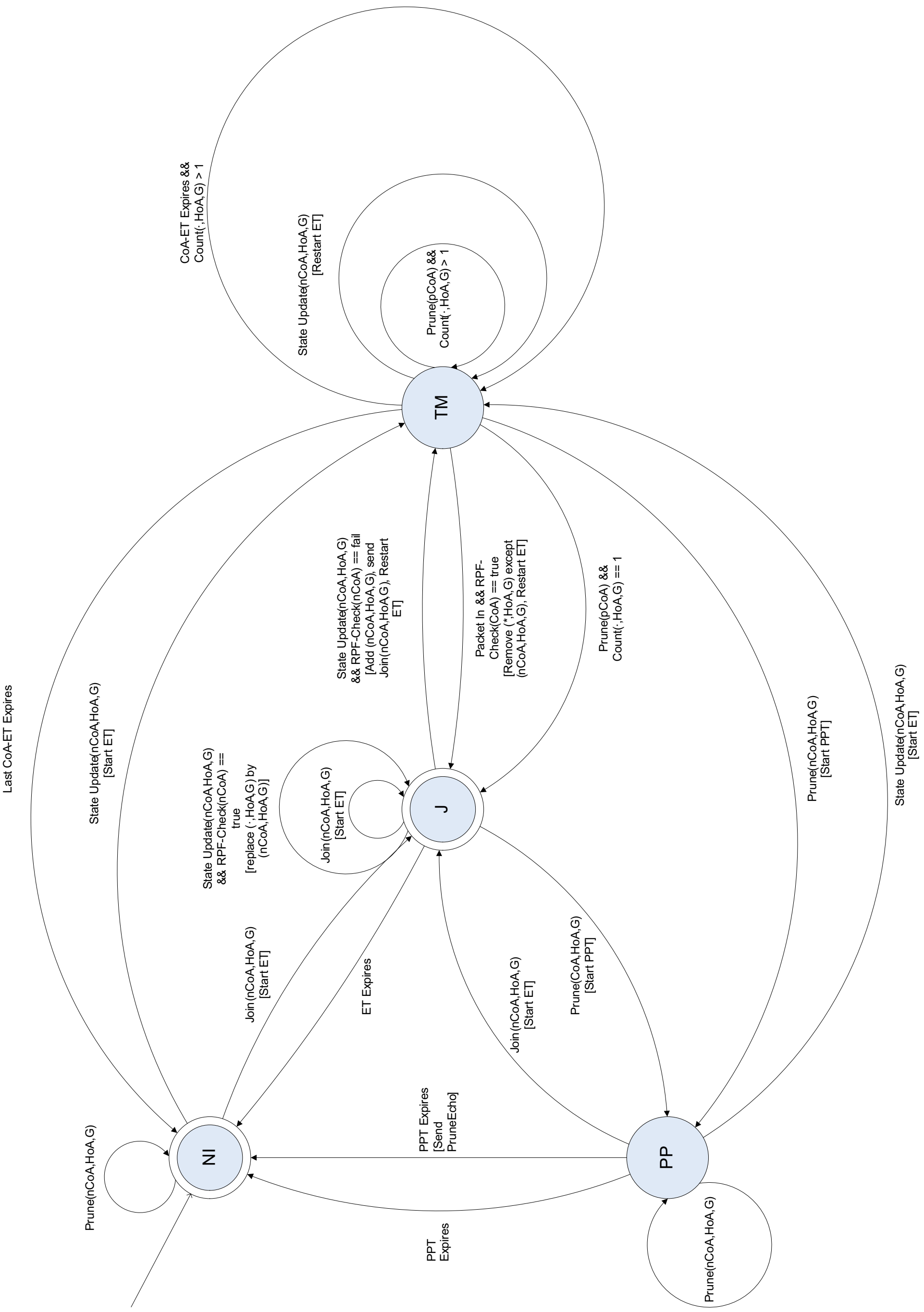
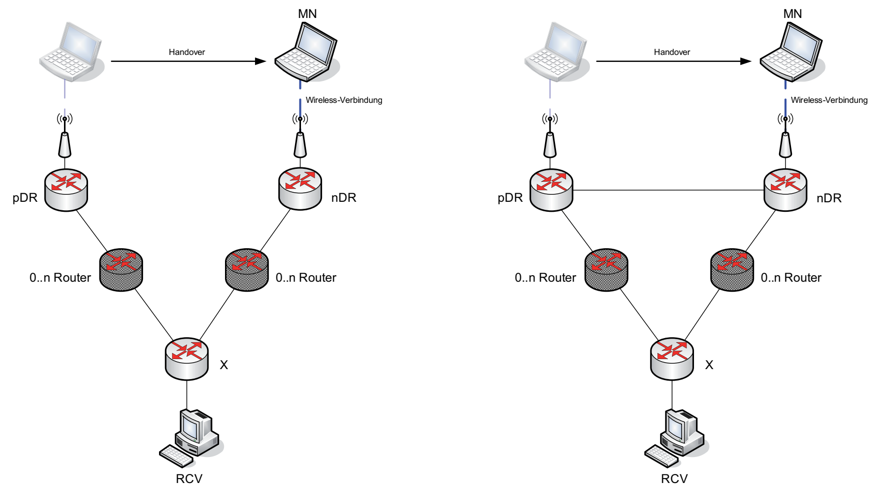


Figure 4 Finite state machine of a downstream interface at Tree Morphing routers



(a) Net 1 (b) Net 2

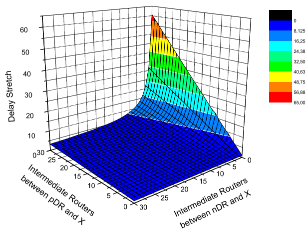
Figure 5 Test Networks Covering the Relative Routing Topology

violations, invalid end states or unreachable states in the design. The working of the J and TM states were observed and found to function as expected.

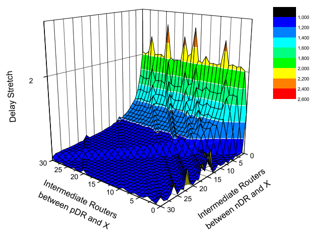
4 Protocol Evaluation

To evaluate the protocol behavior by simulation, we implemented the corresponding functions of routers, sources and receivers within the network simulator platform OMNeT++ 3.3 (Varga et al., 2007) on top of the IPv6Suite, which is based on the INET framework and already realizes MIPv6 protocol operations. We performed a stochastic discrete event simulation, firstly choosing artificial topologies, which explore the attainable relative network geometry, and secondly based on several real–world measurements. In detail, the simulation proceeds as follows: The mobile source continuously submits (numbered and time-stamped) packets at a constant bit rate of $15ms$, while performing a handover from one 802.11 WLAN access point to another. Access points are directly connected to the designated routers. Link delays in our setting have been homogenously chosen to be 10 ms.

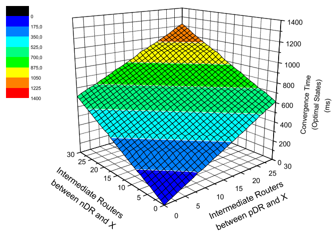
Our analysis covers packet delay, loss and convergence times. Measurements have been performed with the help of a monitoring function at routers and receivers, which accounts for the maximal delay stretch, i.e., the ratio taken of the slowest packet, delivered during handoff, over the optimal transmission time, a surveillance of packet delivery at the receivers, and a state observation for protocol convergence. It should be noted that there are two relevant convergence times. Prior to a full protocol convergence, i.e., final states at all routers, packets may be already delivered on optimal paths. This convergence to optimal forwarding has been monitored separately at the receivers and is displayed in the following analysis.



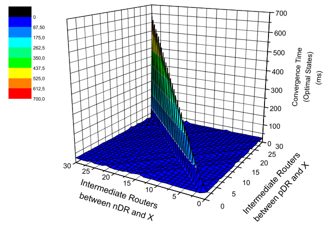
(a) Delay Stretch Net 1



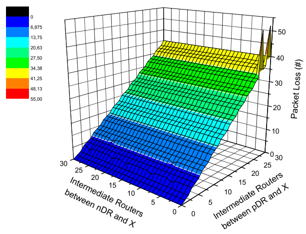
(b) Delay Stretch Net 2



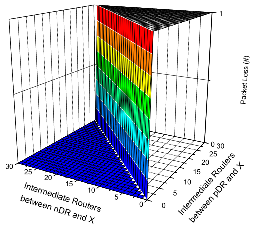
(c) Convergence to Optimal Forwarding Net 1



(d) Convergence to Optimal Forwarding Net 2



(e) Packet Loss Net 1



(f) Packet Loss Net 2

Figure 6 Performance Results for the Test Networks

4.1 Analyzing the Network Topology Space

For a systematic approach to routing analysis, we first proceed in artificially exploring the topology space, i.e., the relative positions of the relevant network entities. The latter are given by the designated routers and the first intersection point (X) of previous and next multicast tree. The degrees of freedom, which only depend on distance ratios, are covered by the two networks displayed in figure 5.

The simulation results for the two test networks as functions of intermediate router hops *DR-to-X chosen between 0 and 30 are given in figure 6. As a striking outcome, test net 2 delivers close to optimal performance. The initial delay stretch, convergence time and packet loss are noticeable only for individual network constellations, i.e., if the routing is required to perform a reorganization of paths between pDR and nDR. Reorganization occurs, whenever the path lengths pDR-X equals nDR-X. Note that the characteristic of the delay stretch derives from the changing optimal forwarding times, while the absolute delay excess stems from one additional hop, i.e., nDR-X. In contrast, test net 1 requires packets to proceed via the path of nDR-X-pDR and a back-signaling from pDR to nDR. This does produce significant additional delay, packet loss and requires up to 1.2 s time to converge to an optimal packet distribution. In this sense, the topology of test net 1 with a large distance from pDR to the intersection X can be seen as a worst case scenario for the TM protocol.

4.2 Real-World Topologies

To approximate realistic scenarios, further protocol evaluations have been performed on the basis of topologies measured in the real world. Such selection of network data 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 (Heckmann et al., 2003) as a large (154 core nodes), densely meshed single provider example. For multiple provider Internet data we extracted a sub-sample of 1.540 core nodes from the "SCAN + Lucent" map project by Govindan and Tangmunarunkit (2000), further on denoted as "Internet" topology. In each simulation, 90.000 uniform samples of pDR, nDR and receivers have been selected within the networks.

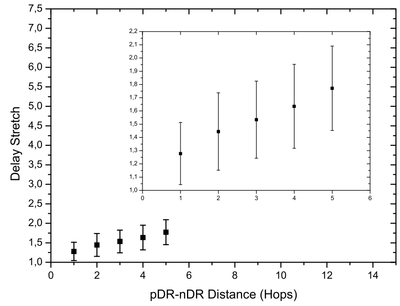
Mean performance results are shown in figure 7 as functions of pDR-nDR distance.[b] In both simulated networks, delay stretch remains minimal and well below 2. Fluctuations as indicated by the error bars are however large for the Internet topology and reflect the wide topological variation met in the inhomogeneous network.

Further on, the homogeneous ATT mesh causes a rapid protocol convergence within a few milliseconds, whereas values for the Internet topology extend up to 1 s. These values increase linearly with the pDR-nDR distance and affirm the characteristic measure. Note that an access router distance of 15 hops is considerably large for real scenarios, where handovers happen in geographic proximity.

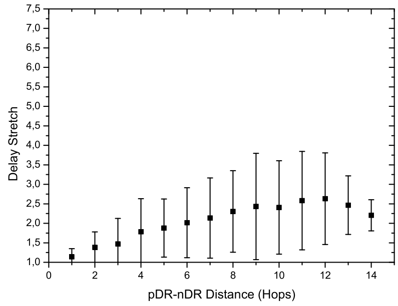
Packet loss remains almost absent in the ATT topology, while interprovider transitions in the Internet topology may lead to a dozen discarded packets. Like in our artificial test networks, losses are experienced, whenever the transition between pDR and the first tree intersection point is large. A realistic scenario for such topological settings is met at handovers between providers with transition at some peering point located far away.

These results, which are caused by mixing topological effects, reflect a promising, but diverse picture. Following a handover in real-world scenarios, packets will arrive at receivers with little additional delay, thus producing limited jitter and disturbances. Protocol convergence likewise occurs at a fast rate, even though it plays a less prominent role at satisfactory packet forwarding. On the other hand, packet loss does grow to an extend, where applications may degrade performance and users are alienated. Thus the latter performance values must be considered a significant flaw in the performance of the Tree Morphing protocol.

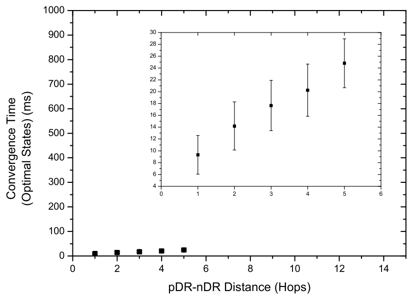
[b]The access router distance, the mobility 'step size' in a figurative sense, can be regarded as a measure of complexity inherent to the problem Schmidt and Wählisch (2006). Values range up to 14 in the Internet topology sample, while the maximum router distance within the ATT network is 5.



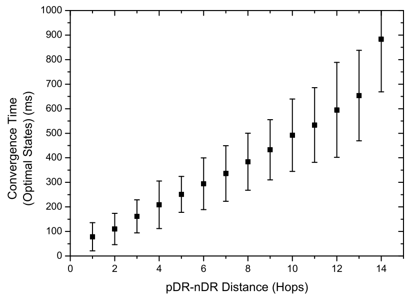
(a) Delay Stretch (ATT)



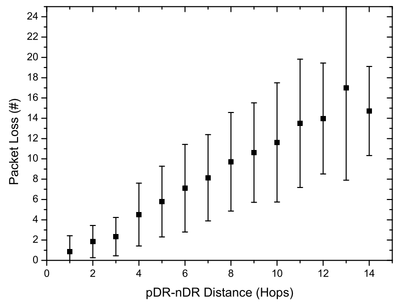
(b) Delay Stretch (Internet)



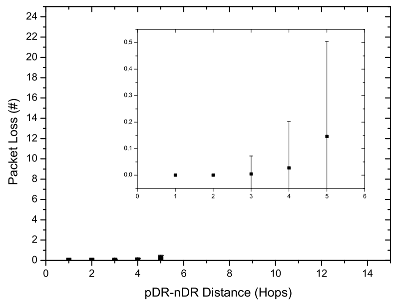
(c) Time to Optimal Forwarding



(d) Time to Optimal Forwarding



(e) Packet Loss



(f) Packet Loss

Figure 7 Performance Results for Real-World Topologies of 154 (ATT - left) and 1.540 (Internet - right) Core Nodes. Error Bars Indicate Standard Deviations

5 Conclusions and Outlook

In this work we have discussed the problem and solution space of source mobility in SSM, taking the special focus on adaptive tree management. We presented a design and a thorough evaluation of the Tree Morphing protocol, which led to divergent results. On the one hand, packet delivery subsequent to handovers admits rather seamless performance. This should be seen in contrast to additional delays of several seconds for unassisted handovers. On the other hand, packets throughout a (real-time) interval of about 200 ms were seen to be lost under certain circumstances. Recalling that 100 ms of voice traffic corresponds to a spoken syllable, this is considered painful.

Even though encouraging, these results are taken as a challenge to further improve the protocol. Optimizations may stem from an immediate identification of the tree intersection points, leading to an expedited protocol adaption to the underlying topology. Such an Enhanced Tree Morphing protocol should comply with similar performance values in packet delays, but avoid loss whenever possible and will be presented in a forthcoming publication Schmidt et al. (2008c).

Acknowledgment

We are grateful to Bettina Buth for her advice and helping hands in the formal protocol verification. This work has been supported in part by the German Bundesministerium für Bildung und Forschung within the project *Moviecast* (http://moviecast.realmv6.org).

References

Arkko, J., Vogt, C., and Haddad, W. (2007). Enhanced Route Optimization for Mobile IPv6. RFC 4866, IETF.

Aura, T. (2005). Cryptographically Generated Addresses (CGA). RFC 3972, IETF.

Chang, R.-S. and Yen, Y.-S. (2004). A Multicast Routing Protocol with Dynamic Tree Adjustment for Mobile IPv6. *Journ. Information Science and Engineering*, 20:1109–1124.

Deering, S. and Hinden, R. (1998). Internet Protocol, Version 6 (IPv6) Specification. RFC 2460, IETF.

Deering, S. E. (1989). Host Extensions for IP Multicasting. RFC 1112, IETF.

Fenner, B., Handley, M., Holbrook, H., and Kouvelas, I. (2006). Protocol Independent Multicast - Sparse Mode (PIM-SM): Protocol Specification (Revised). RFC 4601, IETF.

Govindan, R. and Tangmunarunkit, H. (2000). Heuristics for internet map discovery. In *Proceedings IEEE INFOCOM 2000*, volume 3, pages 1371–1380, Piscataway, NJ, USA. IEEE Press.

Heckmann, O., Piringer, M., Schmitt, J., and Steinmetz, R. (2003). On Realistic Network Topologies for Simulation. In *MoMeTools '03: Proceedings of the ACM SIGCOMM workshop on Models, methods and tools for reproducible network research*, pages 28–32, New York, NY, USA. ACM Press.

Holbrook, H. and Cain, B. (2006). Source-Specific Multicast for IP. RFC 4607, IETF.

Holzmann, G. J. (1991). *Design and Validation of Computer Protocols.* Prentice Hall.

Holzmann, G. J. (1997). The Model Checker SPIN. *IEEE Transactions on Software Engineering*, 23(5):279–295.

Jelger, C. and Noel, T. (2002). Supporting Mobile SSM sources for IPv6 (MSSMSv6). Internet Draft – work in progress (expired) 00, individual.

Johnson, D. B., Perkins, C., and Arkko, J. (2004). Mobility Support in IPv6. RFC 3775, IETF.

Kellil, M., Romdhani, I., Lach, H.-Y., Bouabdallah, A., and Bettahar, H. (2005). Multicast Receiver and Sender Access Control and its Applicability to Mobile IP Environments: A Survey. *IEEE Comm. Surveys & Tutorials*, 7(2):46–70.

O'Neill, A. (2002). Mobility Management and IP Multicast. Internet Draft – work in progress (expired) 01, IETF.

Partridge, C. and Jackson, A. (1999). IPv6 Router Alert Option. RFC 2711, IETF.

Romdhani, I., Bettahar, H., and Bouabdallah, A. (2006). Transparent Handover for Mobile Multicast Sources. In Lorenz, P. and Dini, P., editors, *Proceedings of the IEEE ICN'06*. IEEE Press.

Rosenberg, J., Schulzrinne, H., Camarillo, G., Johnston, A., Peterson, J., Sparks, R., Handley, M., and Schooler, E. (2002). SIP: Session Initiation Protocol. RFC 3261, IETF.

Schmidt, T. C. and Wählisch, M. (2005). Extending SSM to MIPv6 — Problems, Solutions and Improvements. *Computational Methods in Science and Technology*, 11(2):147–152. Selected Papers from TERENA Networking Conference, Poznań, May 2005.

Schmidt, T. C. and Wählisch, M. (2006). Morphing Distribution Trees – On the Evolution of Multicast States under Mobility and an Adaptive Routing Scheme for Mobile SSM Sources. *Telecommunication Systems*, 33(1–3):131–154.

Schmidt, T. C. and Wählisch, M. (2008). Group Conference Management with SIP. In Ahson, S. and Ilyas, M., editors, *SIP Handbook: Services, Technologies, and Security*, pages 123–158. CRC Press, Boca Raton, FL, USA.

Schmidt, T. C., Wählisch, M., Christ, O., and Hege, G. (2008a). AuthoCast — a mobility-compliant protocol framework for multicast sender authentication. *Security and Communication Networks*, 1(6).

Schmidt, T. C., Wählisch, M., and Fairhurst, G. (2008b). Multicast Mobility in MIPv6: Problem Statement and Brief Survey. IRTF Internet Draft – work in progress 05, MobOpts.

Schmidt, T. C., Wählisch, M., and Wodarz, M. (2008c). ETM - An Optimized Routing Protocol for Mobile SSM Sources. In Mammeri, Z. and Diaz, M., editors, *Wireless and Mobile Networking*, volume 284 of *IFIP International Federation for Information Processing*, pages 29–40, Berlin Heidelberg. Springer Verlag.

Thaler, D. (2001). Supporting Mobile SSM Sources for IPv6. Proceedings of ietf meeting, individual.

Varga, A. et al. (2007). The OMNeT++ discrete event simulation system. http://www.omnetpp.org.

Wählisch, M. and Schmidt, T. C. (2007). Exploring the Routing Complexity of Mobile Multicast - A Semi-empirical Study. In *CoNEXT '07: Proceedings of the 2007 ACM CoNEXT conference*, pages 1–2, Columbia University, NY. ACM.