Visualizing the Global Topology of the MBone

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Abstract

We present a case study of visualizing the global topology of the Internet MBone. The MBone is the Internet's multicast backbone. Multicast is the most efficient way of distributing data from one sender to multiple receivers with minimal packet duplication. Developed and initially deployed by researchers within the Internet community, the MBone has been extremely popular for efficient transmission across the Internet of real-time video and audio streams such as conferences, meetings, congressional sessions, and NASA shuttle launches. The MBone, like the Internet itself, grew exponentially with no central authority. The resulting suboptimal topology is of growing concern to network providers and the multicast research community.

We create a geographic representation of the tunnel structure as arcs on a globe by resolving the latitude and longitude of MBone routers. The interactive 3D maps permit an immediate understanding of the global structure unavailable from the data in its original form as lines of text with only hostnames and IP addresses. Data visualization techniques such as grouping and thresholding allow further analysis of specific aspects of the MBone topology. We distribute the interactive 3D maps through the World-Wide Web using the VRML file format, thus allowing network maintainers throughout the world to analyze the structure more effectively than would be possible with still pictures or premade videos.

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1 Introduction

The Internet is evolving to support a variety of distribution models and carry a much broader range of traffic than was traditionally available, in particular multimedia services such as real time audio and video. Multicasting, a network distribution methodology which efficiently transmits data to multiple receivers, is now being widely deployed to solve some of the problems inherent in these new services [5]. Some current uses of the MBone include distributing audio and video streams of conferences, seminars, interactive meetings, and media events. It may see increasing usage as a communication mechanism for networked multi-user 3D applications.

Production Internet routers are only recently beginning to support native multicast. The MBone was designed to provide interim support by using virtual logical links between multicast-capable routers that cross over non-multicast capable infrastructure. Endpoints of these virtual links, or *tunnels*, encapsulate multicast packets into normal IP packets and route them to other multicast capable subnets over the unicast path between the tunnel endpoints. Tunnel endpoints are typically Unix workstations with IP multicast support, using the multicast routing daemon `mrouted`. `mrouted` runs a multicast routing protocol that dynamically manages a spanning tree over the links in the MBone. This tree ensures that data is sent only once across each multicast link, replicated only as necessary when the spanning tree splits into multiple paths.

The MBone, like the Internet itself, grew without planning from a central authority, and shares many of the strengths and weaknesses of the larger Internet. Setting up a tunnel requires minimal coordination, and absolutely no approval by or even informing of other network operators or users, including one's own Internet service provider. Establishing a tunnel requires only that two sites already connected via the Internet exchange IP addresses and configure their machines as endpoints for a tunnel between them. This flexibility has the advantage of facilitating ubiquitous participation without third-party authorization. However, it has also inadvertently spawned an increasingly convoluted and redundant topology, where several copies of the same multicast traffic sometimes travel over the same physical link.

As the size of the MBone grows and Internet congestion becomes increasingly problematic, there is greater incentive to tune tunnel placement to provide the most efficient distribution topology and minimize the imposed Internet workload. Ideally, tunnels should be placed so that they travel along uncongested links that carry no other tunnels. The rapidly changing nature of Internet complicates this task. Two hosts that were connected via an uncongested high bandwidth path six months ago may easily be traveling a different more highly congested route today.

Tunnel placement should match the structure of the existing unicast Internet topology whenever possible, and only traverse non-multicast capable infrastructure long enough to get to the nearest available multicast capable subnet. In practice, however, tunnels have been used to create an overlay network that in some places is disjoint from the underlying Internet topology. The multicast routing protocol determines the shortest paths in its spanning tree based on the tunnel hop count rather than the underlying unicast hop count, resulting in sub-optimal distribution of multicast data.

Given the increasing popularity of the MBone among Internet users and the potential impact of tunnel traffic on the production Internet, Internet service providers (ISPs) are beginning to recognize issues associated with large scale multicast distribution. Providers trying to offer multicast services or engineer transit tunnel traffic currently have very few tools with which to analyze the overall system or the role of their own infrastructure within it.

This inability to effectively understand and manage the MBone, whether by the users, providers, or multicast researchers, is the underlying motivation for our desire to visualize its global structure.

2 Methodology

A few years ago the MBone was a new and small enough system that it that maintaining detailed maps of its topology did not require a sophisticated infrastructure. The early map generating efforts, which culminated in a four-page PostScript printout requiring hand-tiling, were abandoned in mid-1993 [1]. Since then, the topology of the MBone has only been available through lists of tunnels and its detailed geography has not been drawn.

We build on the work of researchers at the University of Cambridge, who maintain a publicly available list of the topology of the MBone [4]. This data is generated by the `mwatch` program developed at University College London which lists the IP addresses (and often hostnames) of multicast routers at tunnel endpoints. We have augmented the Cambridge list with information about MBone routers in some of the firewalled private networks.

Hidden within this large data set are highly suboptimal tunnel placements, misconfigurations, and outdated parts of the MBone topology that should be removed. However, without effective visualization tools, it is almost impossible to sort through this set and derive conclusions about how to improve the current configuration. As of June 1996, the MBone topology data set consisted of over 75 pages of textual data as shown in Table 1.

Since the end goal is to analyze and improve the distribution efficiency of the MBone overlay on the Internet, the most effective method would be to draw the tunnels as segments corresponding to each unicast hop the tunnel traverses. However, determining the unicast path would require dealing with a much larger volume of connectivity information as well as determining the current routing policies of the major providers, a prohibitive task at this point.

We therefore made the simplifying assumption that the logical unicast topology was closely related to the physical geography, and use a geographic-based visualization to draw conclusions about the overall structure. Figure 1 shows a 3D interactive map of the MBone tunnel structure.

There has been previous work in geographical network visualization, most prominently by Eick *et al.* at Bell Labs. This group has presented the 2D interactive SeeNet system for realtime visualization of telephone networks and offline visualization of Internet traffic [2]. The more recent SeeNet3D system visualizes worldwide Internet traffic using a visual metaphor of arcs on the globe [6]. Our current work uses the same visual metaphor, but in a different context. The influential work of Cox and Patterson at NCSA was a videotape rather than interactive software.

This paper is a case study: our primary goal is incremental progress toward solving a real world problem using appropriate visualization techniques. Our contributions include the construction of an accurate database of locations indexed by IP address and domain name, and an extension of the "arcs on globe" representation to include hypertext links in the 3D representation of the arcs.

3 Geographical Determination

In order to construct the geographical representation, we need to obtain the latitude and longitude that corresponds to the IP address of each MBone router. The Pablo project at UIUC has also investigated geographic-based network visualization, displaying bars on the globe to represent traffic from the UIUC Web server to individual cities [8]. Under the presumption that most of the client sites are in domains that represent a single location, they used the InterNIC domain database to map the domain name to the location registered in the database when the domain name was assigned.

Since by nature many important MBone nodes belong to transit providers covering a wide geographic area, InterNIC-registered addresses for domain names are not an accurate

> multe.uib.no(129.177.13.20)	lilja.uib.no(129.177.11.224)	[1/6/tunnel/down/leaf]
> multe.uib.no(129.177.13.20)	gwaihir.zi.uib.no(129.177.64.13)	[1/6/tunnel/down/leaf]
> multe.uib.no(129.177.13.20)	munin.hf.uib.no(129.177.207.20)	[1/6/tunnel/leaf]
: cs2.slu.se(130.238.118.1)	11.0,mtrace	-4885
> cs2.slu.se(130.238.118.1)	ultrouter5.slu.se(130.238.118.2)	[1/0/pim]
: lab-1-rtr-S0.InterNex.Net(205.158.1.18)	11.1,prune,mtrace,snmp	-1061037
= lab-1-rtr-S0.InterNex.Net(205.158.1.18)	205.158.3.209(205.158.3.209)	
> 205.158.3.209(205.158.3.209)	INADDR_ANY(0.0.0.0)	[1/0/pim/querier/leaf]

Table 1. example MBone topology data from University of Cambridge

Figure 1. A 3D interactive map of the MBone tunnel structure, drawn as arcs on a globe. The endpoints of the tunnels are drawn at the determined geographic locations of the MBone router machines. In this and all figures not otherwise labeled, we draw nearly 700 of the 4400 tunnels comprising the MBone on June 15, 1996. Over 3200 are not drawn because we have determined the endpoints to be co-located, while the remainder are ignored because we were unable to find their geographic position. The text window below shows the hostname, city and state/country name, latitude, and longitude of the endpoints of the selected tunnel. A URL pointing to this information is bound to the 3D representation of each tunnel.

source of accurate host location data. Hosts of large administrative entities such as backbone providers are often the most critical in building a true picture of network usage. Even client domains, e.g., `nist.gov`, `csiro.au` or `in2p3.fr`, can encompass several different campuses within an organization.

Given the absence of any generally applicable mapping, we have been constructing a database of latitudes and longitudes indexed by IP address and domain name, using a collection of manually intensive methods including the InterNIC database, traceroutes, network maps, Web searches, personal knowledge about organizations and network structure, and personal communication.

Our visualization system itself has proven itself useful in the detection of anomalies in these geographic mappings; clicking on a tunnel in the 3D scene triggers the display of hypertext information about its endpoints, providing a useful feedback loop.

Since it is unlikely in the short term that each network node will be able to self-determine its geographic location, visualizations like this one still depend on parties such as ourselves to build and maintain a database of mappings, or administrators at each site volunteering to provide/maintain current geographic information.

Even with no general automatic solution, the networking infrastructure can facilitate this process by providing mechanisms for the transport and indexing of bindings between network entities and geographic, administrative, and logical location. One of the co-authors (BF) is involved with MBone tool development, and is adding such a reporting mechanism to the next generation of MBone tools in order to facilitate further visualization work. Although these options require that the router administrator manually configure the geographic location during router configuration, we hope that administrators will comply in the spirit of cooperation.

One potential long term solution it to attempt to harness the interest of the Internet community itself. We distribute our database both to assist others performing similar visualizations, and to encourage people that know about particular sites to submit corrections and additions. We have made the hostname-geography database available through the NLANR Planet Multicast Web site [10], This site also houses 3D VRML interactive maps of the current state of the MBone, automatically updated nightly, as well as the tools used to create these maps from the original Cambridge database.

4 Visualization

The driving force behind our work is the desire to solve a real problem: understanding the geography and topology of the MBone in order to keep it from breaking. Since repair will require the cooperation of many MBone users and system administrators around the world, a fundamental goal of the project is to make the interactive 3D maps available to as many people as possible.

4.1 VRML

In pursuit of this objective, we chose to use the VRML 1.0 (Virtual Reality Modeling Language) format for distributing 3D data with embedded hyperlinks across the World Wide Web [3]. VRML popularity is growing quickly, and there are already many 3D browsers available for a wide variety of platforms [7]. By making our 3D maps available on the Web as VRML files, we allow the MBone community to interactively explore the MBone structure. We believe that disseminating 3D data files will lead to a clearer understanding of the problems and possible solutions than merely distributing still pictures or even videos.

We thus use a VRML 3D visualization system to display the tunnels as arcs on a globe. The VRML support for hypertext allows us link the graphical representation of each tunnel to a textual description. The user can determine the specific administrative endpoints that correspond to a given tunnel by clicking on the tunnel in the 3D viewer. The link points to hypertext that contains the IP address, hostname, location (city/state/country), and latitude and longitude of the tunnel endpoints.

The visualization engine used for most of our development has been done on an adaption of the WebOOGL 3D Web browser [11], built on top of the Geomview platform [12]. Most VRML browsers do not support interactive changes of color, linewidth, and position on a per-group basis. In fact, the VRML 1.0 file format does not facilitate per-group interactions (this restriction is will be lifted in future VRML 2.0 systems). The WebOOGL/Geomview system uses a different Web-enabled file format internally, which we convert into VRML. We use the Geomview-based visualization system to dynamically change values until we arrive at a useful configuration. We can then feed these values back into the grouping and visualization construction phase to create distributable VRML files. The Geomview-based system also visually highlights the selected tunnel in the 3D scene through color and linewidth changes, in addition to showing the hypertext information in another window.

We use a globe constructed by Stuart Levy of the Geometry Center using the CIA World Map database. We draw outlines of the continents on a solid-colored sphere rather than using a texture map of the real Earth to reduce both computational requirements and extraneous visual clutter. Most of our development work is on SGI platforms. The VRML files that we disseminate use a lower resolution version of the outlines, so that lower-end systems can maintain reasonable frame rates during interaction.

4.2 Arc Height

We construct the arcs on the globe using the hostname/latlong for the endpoints of each tunnel in the database described above, and compute the shortest geodesic arc between those lat/longs on the Earth's sphere. Using the endpoints of the spherical geodesic as the endpoints of the arc, we loft the arc above the surface of the sphere. The height of the arc depends on the length of the geodesic, using essentially the same equation as the SeeNet3D system [6]. We briefly experimented with using the same height for all arcs, but the display quickly became very cluttered. Having the arc height depend on its length lends visual emphasis to long arcs, an advantage for our application since we want inordinately long tunnels to stand out. Likewise, short tunnels are least obvious, which is appropriate since such tunnels impact global congestion the least. We also impose a minimum arc height requirement so that even very short tunnels remain visible.

4.3 3D Navigation

Although the geographic representation of the data is vastly easier to comprehend than the raw textual form, the current MBone structure is sufficiently complex that further visualization techniques are desirable. We made a similar set of visualizations using lines on a two dimensional projected map of the earth, and found that the lines representing the tunnels were far too dense to allow for interpretation. The move to the globe-based three dimensional representation gave the display much more locality and enhanced the users ability to selectively display tunnels. The user can rotate, translate and zoom to focus on an area of interest. We have found that the capability to change the center of rotation from the center of the earth to a user-chosen point on its surface to see a "horizon view" of the tunnels (as in Figure 2), is particularly helpful to understand local structure of the shorter tunnels.

Figure 2. We highlight the few MBone tunnels participating in PIM, a more advanced (but still not operationally stable) unicast routing protocol-independent multicast routing protocol. Three visualization techniques are used in this figure: distance-based arc height, 3D navigation and grouping. The "horizon view" results from zooming close and clicking on a point on the earth's surface to act as the center of rotation. Moving our eyepoint close to the earth also emphasizes the different arc heights. Finally, the PIM tunnels are drawn with a different color and linewidth than the default grouping.

4.4 Thresholding

We have implemented thresholding in order to reduce the visual clutter. Figure 3 shows a thresholded view where we clip the tunnel drawing to a radius around the endpoints. Once again, this is particularly useful when focusing on local rather than global structure.

4.5 Grouping

Finally, grouping allows us to visually distinguish between categories of tunnels. We use a regular-expression based filter which allows us to categorize based on any text attribute of the original data. For example, in Figure 2 we group based only on the "info" field of the tunnels. We use a more powerful filter in Figure 7 which categorizes across multiple fields, in this case both the source and destination hostnames. We can visually distinguish these groups by color and linewidth, and in sufficiently flexible 3D viewers can move a group in relation to the other 3D data. While such motion of course dislocates the tunnels from their geographic reference points on the globe, which would be very disorienting for a single tunnel, it can be very useful when comparing tunnel groupings complex enough that the tunnels alone connote geographic structure.

Figure 3. Only the segments within a user-defined radius around the tunnel endpoints are drawn in this thresholded view, which reveals local details hidden in Figure 4.

5 Results

The most obvious conclusion about the general character of MBone deployment is that areas with fewer network resources and limited numbers of redundant links seem to have more efficient tunnel placements. The European tunnel structure shown in Figure 4 is much closer to a hierarchical distribution tree than the that of the United States.

The recent privatization of the Internet has led to the fragmentation of the former hierarchical US structure. Figure 7 classifies tunnels by domain status, as to whether one, both, or no endpoints belong to a major Internet Service Provider. Note that most, but certainly not all, of the cross-country links have one or both ends on a backbone. In Figure 6 we further categorize tunnels for which at least one endpoint host belongs to one of the major backbones. We see that although there are many tunnels between the East and West Coast, each provider, when taken alone, has an appropriate amount of redundancy. Nevertheless, from the broader view, the large number of tunnels all carrying the same information between the coasts is not the most optimal use of limited Internet resources.

All figures thus far have shown the MBone on the same day. Figure 5 compares the changes in the MBone across a four-month period of time. In both figures we highlight the Sprintlink tunnels and focus on Texas. We see that in

Figure 4. Two regional closeup views of the MBone. The United States tunnel structure above is quite redundant compared to the European structure below. Reducing number of coast-to-coast tunnels would reduce offered workload to the often congested underlying unicast infrastructure. All of these tunnels may be carrying identical data.

February Texas A&M University has configured a tunnel to a Sprint hub in Washington DC. Notice that by June Sprint has extended their tunnel support to a major hub in Fort Worth, but the university has not leveraged the new topology and still uses the now suboptimal Texas-to-DC tunnel. Such configurations are much easier to see with the geographic visualization than with the raw text data.

6 Conclusion and Future Directions

The deployment of a system such as the MBone should be a careful balance between distribution efficiency, resource availability, redundancy in case of failure, and administrative policy. We hope that this series of visualizations and continued work in this area will help ISPs and administrators of campus networks cope with a growing infrastructure by illustrating where optimizations or better redundancies could occur within and across network boundaries. This process has already begun: when our co-author involved with MBone deployment (BF) saw the initial 3D visualization in February 1996, he was inspired to encourage many maintainers of suboptimal tunnels to improve their configuration.

Figure 5. A view of the MBone tunnel structure in Texas at two different times: above is February 12, 1996, below is June 15, 1996. Tunnels in the Sprintlink network are drawn in thicker dark arcs in both, and the selection of a tunnel between Texas A&M University and Washington, DC is shown with a very thick black arc. We see that altough Sprint has established a major new hub very close to TAMU, that closer source is still unleveraged in June.

Visualization of the MBone has provided important insight into the existing MBone structure as well as specific problems in the current distribution framework. The 3D visualizations are far more useful for people working in the MBone engineering process than the textual data, and can serve as an educational medium for the general public. However, their interpretation requires a great deal of operational context and they could be misleading for those without a broad understanding of the underlying technologies.

Both the visualization techniques and the geographic mappings that we have developed are valuable tools for the visualization of other network topologies. These tools have also been applied successfully to other domains such as the hierarchical WWW caching system, wide area Internet routing, and congestion measurement. We hope that these visualizations will encourage network providers to make available geographic, topological, and performance information for use in visualizations that could facilitate Internet engineering on large and small scales.

One possible future direction is to create an animation of the evolution of the structure over time using tunnel data archived at regular intervals. Interactive analysis of larger scale topologies, such as the mapping of the MBone onto the underlying unicast framework, or investigating general unicast Internet routing problems, will require a broader set of visualization and data collection techniques. Both general level of detail control and additional layers of abstraction will be critical for interactive manipulation of a structure of this complexity. We would also like to explore other visual metaphors. One strong advantage to our current "arcs on globe" geographical layout is that viewers understand it immediately with little explanation. The disadvantage is that tunnels between co-located machines are not shown. A graph embedding where edge length and internode distance are determined by some other data can be a very effective medium for conveying a different understanding of the properties of interest. Such a representation, not tied to the geography of the Earth, is amenable to display in 3D hyperbolic space [9]. However, it can be quite a challenge to obtain the relevant data for many network attributes, for instance delay variation as a metric of goodness.

Another interesting possible use for the tools we have developed is to manage the deployment of the next generation IP protocol, version 6 (IPv6, sometimes referred to as IPNG). Developed over the past two years to address specific engineering concerns related to scalability and packet processing, IPv6 is now approaching standardization, and service providers and network architects are beginning to consider the steps involved in a graceful transition to this new routing and forwarding infrastructure. During the transition tunnels will serve to lash together sections of the new IPv6 Internet, analogous to those that form the MBone today. Appropriate visualization will be extremely valuable in the management of this dynamic Internet-wide migration process.

7 Acknowledgments

We would like to thank the many people who helped us resolve geographic bindings for their regions. We also thank Pat Hanrahan and the anonymous reviewers for their comments on an earlier draft of this paper. This material is based on work partially sponsored by the National Science Foundation under NSF Cooperative Agreement NCR-9415666 and the NSF Graduate Research Fellowship Program.

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Figure 6. MBone tunnels of the major backbone networks, colored by provider: MCI in red, Sprintlink in cyan, NASA in blue, ESnet in green, Dartnet in magenta, BBNPlanet in yellow, and ANS in white. All other tunnels are drawn in thin black lines.

Figure 7. MBone tunnels grouped by backbone status: black tunnels have a major provider at both ends, blue tunnels have one endpoint which is a backbone, and neither endpoint of a red tunnel is attached to one of the backbones. The first three views each show a single group drawn with thick lines, while the last shows all groups equally emphasized.