

Collecting and Modeling the Join/Leave Behavior of Multicast Group Members in the MBone*

Kevin C. Almeroth and Mostafa H. Ammar
College of Computing, Georgia Institute of Technology
Atlanta, Georgia 30332-0280
{kevin,ammar}@cc.gatech.edu

Abstract

*One purpose of the MBone is to study the performance of multicast and real-time protocols in global conferencing applications. Part of this evaluation is dependent on understanding how the MBone is used and developing realistic workloads and usage models to assist in protocol evaluation. We have developed a tool, called *Mlisten*, to accurately collect the join/leave times for multicast group members in MBone audio sessions. Using data collected with *Mlisten* and a set of analysis tools, we report statistics about several MBone audio sessions including member inter-arrival times and durations, multicast tree routing information, and group spatial characteristics. Data was also collected and analyzed for all active sessions to produce information about movement among multicast groups.*

1 Introduction

The Multicast Backbone (MBone) is a virtual network overlaying the Internet[3]. It provides one-to-many, best effort delivery of real-time multimedia data between MBone-connected hosts. The MBone has served as a testbed for the development of multicast protocols, real-time protocols, and group conferencing tools. As the MBone has evolved over time, it has come to provide a relatively stable platform for the world-wide delivery of seminars, conferences, working group meetings, and some entertainment programs. As such, the MBone represents a good first estimate of how multicast services will be used when the Internet becomes entirely multicast capable.

Of particular interest, and the focus of this paper, is the real use of multicast communication (over the MBone infrastructure) to broadcast events on a very large scale. Insight is gained by observing and characterizing the behavior

of MBone session members. Collecting and analyzing the join/leave behavior is of great benefit in understanding how any future networking infrastructure with multicast and real-time capabilities will be used. More fundamentally, basic statistics and an understanding of changes in group membership and characteristics are useful for developing and testing more efficient multicast routing and resource reservation algorithms and protocols. Furthermore, the ability to collect data and build workload traces and models is a useful result of this research.

The MBone behavior we are most interested in is based on the scheduling of world-wide MBone “events” which are typically announced ahead of time in a global session directory[13, 11]. Using information in this session directory, interested people can join multicast groups and receive real-time audio and/or video streams. Our primary interest lies in monitoring the rate at which people join each session and the duration of membership. To this end we have developed a tool, called *Mlisten*, to monitor MBone sessions and collect behavior statistics. This collected data is then analyzed to produce (1) basic statistics about group size and membership turnover, (2) information about the temporal and spatial dynamics of the multicast group, and (3) user join/leave behavior workloads and models.

This paper documents our specific efforts in three areas. The first is the capture of accurate MBone usage data. This involves building a collection tool and pre-processing raw data to eliminate “noise”. The second effort is the characterization and analysis of single sessions. For single sessions we concentrate on understanding membership characteristics and group turnover. The third effort is an analysis of data collected for all active sessions. This data allows us to track members who are in multiple groups simultaneously or who “surf” among the set of active sessions.

We are not aware of any similar work aimed at collecting MBone multicast group membership or using this data to create behavior workloads or models. Nevertheless, our work is related to a body of work aimed at understanding the operation of the MBone. Such efforts include debugging

*The measurement tool, called *Mlisten*, is available at <http://www.cc.gatech.edu/computing/Telecomm/mbone/>

tools[1, 10, 7] that have been developed to analyze network problems. These tools try to isolate problems by determining routes and the status of links in the MBone. One of these tools[10] was used in our study to approximate the set of MBone links connecting a source to a set of destinations. In the area of traffic analysis, one effort evaluates the volume and types of traffic carried on the MBone[15].

The remainder of this paper is organized as follows: Section 2 gives an overview of the MBone and briefly describes the subset of tools relevant to this paper. Section 3 describes the monitoring tool, data collection and processing. Section 4 presents an analysis of behavior for single sessions. Section 5 analyzes behavior for all sessions. The paper is concluded in Section 6.

2 Conferencing on the MBone

The MBone has been in a constant state of development since its inception in 1992[4]. Connectivity was first provided using point-to-point IP-encapsulated *tunnels* between sites. Each tunnel connects two end-points via one logical link but may cross several Internet routers. Within a particular site, multicast capability has been provided using additional tunnels or the Distance Vector Multicast Routing Protocol (DVMRP)[7, 8]. As the MBone has developed and experience with multicast has grown the use of native multicasting has replaced many tunnels and extends beyond site boundaries. In addition to DVMRP, Protocol Independent Multicasting (PIM)[6, 9] is now being used. The trend and eventual goal of this effort is to one day make the Internet fully multicast capable.

The MBone is being used for a variety of applications but we are most interested in the real-time, one-to-many delivery of the audio portion of globally and near-globally transmitted programs¹. Information about these sessions are periodically transmitted over the MBone on a well-known multicast address. Using either SD[13] or SDR[11], MBone users can obtain a list of active sessions. An MBone user can choose from this list and launch the MBone tools (including audio, video, or whiteboard) required to receive the component streams of a session. When any of these tools are started, the user *joins* a multicast group allocated to the particular stream. Once part of the group, members will receive group transmissions and they can actively participate or simply listen.

Of the different media types supported by the MBone, the audio tools are the easiest from which to capture membership statistics. This is because the two most commonly used audio tools, VAT[14] and NeVoT[16], use the same straightforward approach for broadcasting session membership information. Name information is periodically (approximately

every 5 seconds) broadcast by each group member and is used to create a visual list of group members. Other media either do not fully support the exchange of group membership information or are less frequently used in MBone sessions.

Communication in an MBone audio session takes place using an advertised multicast IP address and two pairs of UDP ports. The first pair of UDP ports, the *data ports*, are used to transmit audio; the second pair, the *control ports*, are used to transmit group membership information. Each pair of ports consist of an advertised port number used to receive packets (either control or data), and a local port number used to transmit packets. Each time an audio tool is started, different local port numbers are used. As long as the audio tool is open the host machine will be part of the multicast group. This *membership duration* is one characteristic we try to capture.

3 Data Collection

Accurate data collection involves two components: (1) capturing group membership data, and (2) processing this data to eliminate “noise”. Data capture is obviously done in real-time, while log processing is typically done when the log file is analyzed. The mechanisms for doing both are described next.

3.1 Capturing Usage Data

Our collection tool, *Mlisten*, continuously monitors the well-known multicast address used to advertise sessions. For each audio session, *Mlisten* joins the group and collects information about control and data packets. When a packet arrives, *Mlisten* identifies the packet’s sender, the MBone session, and the time of arrival. This information is used to maintain a list of group members in each session.

At periodic intervals, *Mlisten* searches this list and identifies any group members who either stopped transmitting data packets or who left the group and stopped transmitting completely (including control packets). If no *data* packets are received for a threshold period of two minutes, a “talk period” is assumed to have ended. Similarly, if a group member stops sending packets completely, the member is assumed to have left the group. For the MBone sessions, if there are no group members or session advertisements during a four hour period, the session is assumed to have ended. Any record that has ended is written to a *log file* and includes the following information: (1) the type of record (receive, transmit, or session), (2) the session multicast address and port number, (3) the host IP address and UDP port number, (4) the date and time the first packet was received, (5) the membership duration for receivers or talk-spurt duration for transmitters, and (6) the number of packets received.

¹We collect statistics from a site at Georgia Tech and so are limited to the observation of sessions that reach us.

3.2 Log File Noise Elimination

The log file generated by *Mlisten* may not accurately reflect true group membership or behavior. Two reasons are: (1) unreliable packet delivery, and (2) experimental usage of the MBone. The cause of these two problems and ways of dealing with each are as follows:

Unreliability. Unreliability causes packet loss and delivery jitter which can result in some group members appearing to leave a session, but not actually doing so. Multiple records for the same user showing several group join/leave actions may actually be only one join/leave action that was split because of packet loss.

Verifying the accuracy of the log can be done by comparing IP addresses and UDP port numbers. Each instance of an audio tool uses different port numbers, so log records for the same host should have different UDP port numbers. If the numbers are the same, there is a high probability that the records are for the same join/leave action and should be combined.

Observance of the collected data reveals that sometimes multiple entries for the same host with the same UDP port number are separated by several hours. The obvious reason is that a link between the host and the collection point was down for a long period of time. Another possibility is that a user is running the MBone tools from a location that experienced significant losses in connectivity. In processing the log file, we do not combine records which are separated by more than four hours.

Experimental Usage. Experimentation in the MBone is a problem because it does not reflect *normal* use. Since the goal is to model normal use, we try to eliminate obvious cases where usage is atypical and might skew quantitative analysis. Our working definition of experimental usage is given to be any extremely high rate of requests from a particular host where membership duration is on the order of a couple of seconds. An example of log file processing and the remove of some experimental data is described next.

Figure 1 shows both raw and processed data for the 1995 STS-63 Space Shuttle Mission. Each set of graphs has three parts which include:

- **Number of Receivers:** At five minute intervals, the number of group members is sampled and plotted.
- **Member Inter-Arrival Time:** The time between the arrival of members is plotted.
- **Membership Duration:** When a new member joins the group, the duration is plotted on a log scale.

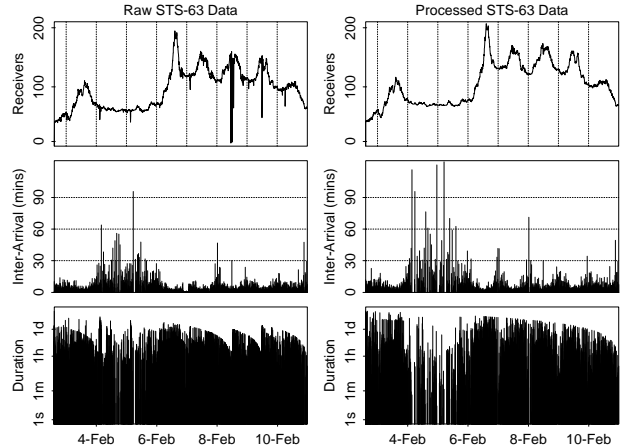


Figure 1. STS-63 temporal statistics.

A more complete analysis of the processed data for single sessions is presented in the next section. However, some important differences between the raw and processed STS-63 data include:

Loss of MBone Connectivity. The raw data has several downward “spikes” in the number of receivers. This can be attributed to either partial or complete loss of connectivity to the MBone. However, these spikes have been eliminated from the processed data using interpolation.

Inaccurate Membership Durations. Because of MBone outages, membership durations in the raw data appears to tail off at the start of each outage. In the processed data, durations only tail off at the end of the measurement period.

Removal of Experimental Data. Several instances of experimental usage were detected and removed. One in particular started on February 6, 1995, at 7:30pm EST and lasted for approximately 6.5 hours. During this period, one particular host joined the session more than 1700 times! Join requests were made once every 10 seconds and membership duration lasted about one second. Because this was obviously not “normal” behavior the group join actions were removed from the processed data. Figure 2 shows a magnified view of the data before it was removed.

4 Analysis of Single Sessions

In this section we present the results of temporal and spatial analysis conducted on data collected for two sessions.² The two sessions are: (1) the STS-63 session from February

²Additional analysis of other sessions can be found in [2].

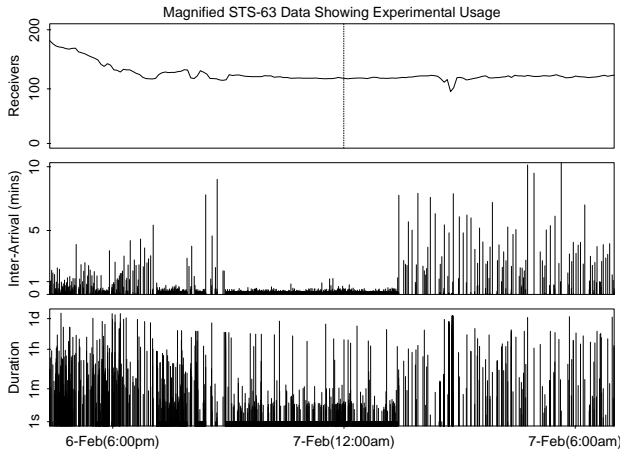


Figure 2. Magnified view of experimental data.

3, 1995, to February 11, 1995, shown in Figure 1 and (2) a UCB Multimedia Lecture Series presentation on February 17, 1995, shown in Figure 3.

4.1 Temporal Statistics

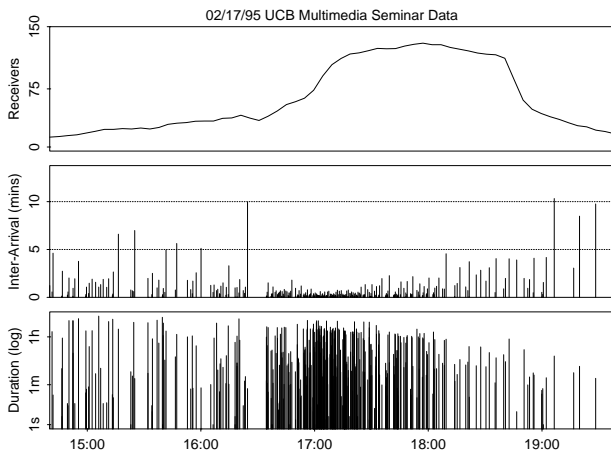


Figure 3. UCB Seminar temporal statistics.

Variations in Activity. For long running sessions (like the STS-63 session) or continuous broadcasts (like the IMS World Radio Network), daily and weekly variations in turnover and participation are quite pronounced. The highest periods of activity occur during the day. Day time hours are based on time zones in the United States because more than half of the receivers are in the United States (see Section 4.3). At night, activity (as measured by the inter-arrival time between new group members) and group size are much lower. Weekends usually see the least amount

of activity. For example, the average inter-arrival time for the entire STS-63 session was 2.5 minutes, but the weekday average was 22.1 seconds; the weeknight average was 3.9 minutes; and the weekend average was 12.6 minutes.

For shorter sessions lasting less than a day or two, turnover and participation are strongly correlate to the advertised start and end time of transmissions. The UCB seminar shown in Figure 3 was a talk that started at 17:30, lasted about an hour, plus another half hour for questions. Most short sessions exhibit an increasing amount of group join activity up to just after a program’s scheduled start time.

Variations in Duration. The membership duration was relatively consistent and well behaved over the lifetime of observed sessions. One interesting observation is that group members typically either join for a very short period of time or stay for the entire session even if the session lasts for many days. For the STS-63 session, the average membership duration was 5 hours, but the median duration was only 6.5 minutes. Furthermore, during the STS-63 session, each host averaged 4.2 join requests suggesting that users would join for a couple minutes several times over the session lifetime.

For a shorter session like the UCB seminar, the average membership duration was much shorter (46 minutes) but the median duration was similar to long sessions (7 minutes). This suggests that there is a much higher turnover for shorter sessions. Finally, there appears to be a relationship between session content and membership duration. During a session, if there is no one transmitting, there is a noticeable decrease in average duration.

4.2 Temporal Data Modeling

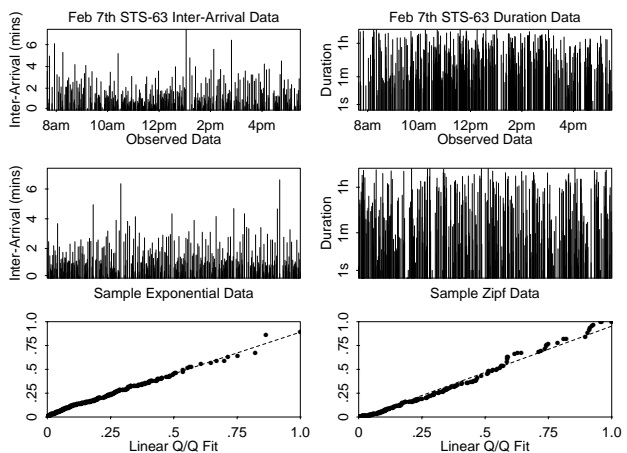


Figure 4. Fit of STS-63 data.

One of the most important aspects of our analysis is fitting collected data to well known distributions. We con-

concentrate on modeling the two temporal aspects of sessions: (1) inter-arrival times, and (2) membership durations. The most significant challenge in accurate modeling long running sessions is handling the daily and weekly variations in activity. For short sessions, problems arise because variations in activity occur around the broadcast start time. The general solution to this problem is to only model a subset of the data. For long running sessions we try to model 8 to 10 hours of data from a typical day. Figure 4 shows the results for the February 7th STS-63 data. For short sessions we have to use a much shorter time period. Figure 5 shows an hour of data centered around the UCB session start time.

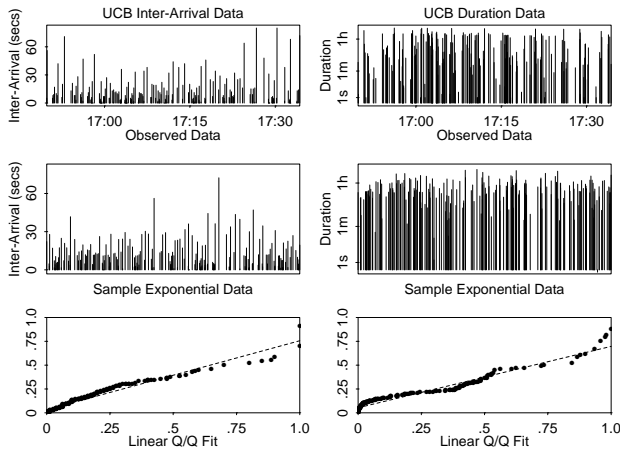


Figure 5. Fit of UCB data.

The results in Figures 4 and 5 show that inter-arrival data for both sessions fit well to an exponential distribution. The STS-63 data fits extremely well except for one or two points at the high end. For membership durations in long sessions, an exponential function does not work because several people join for very long periods. Instead, we use a Zipf distribution which works when a large percentage of (duration) samples are concentrated at the beginning of the range while the remaining percentage are widely dispersed over the remainder of the spectrum[17]. This is exactly the type of behavior exhibited, so a Zipf distribution fits very well. For short sessions, because the maximum membership duration is much shorter and there are no long durations, an exponential function can be used. However, there is still a small tail.

4.3 Spatial Analysis

We use two methods for analyzing the spatial characteristics of an MBone session: (1) the number of hops in the multicast tree, and (2) a geographical breakdown of group members based on domain name.

Multicast Tree Hop Count. In computing the cost of reaching a set of destinations, we consider several types of trees. Our cost metric is that of packet-hops (first used in [5]). For example, a tree from a source to multiple destinations will have a cost in packet-hops equal to the number of links in the tree. The types of trees we consider are:

1. **MBone Tree with Observed Source:** We use the MBone topology and create a source to destination set tree. The routes used are roughly approximated using the MWatch tool[10]. The multicast hop count is compared to a unicast hop count which is computed assuming that the source transmits to each receiver individually (also known as the *separately-addressed packets* scheme [5]).
2. **MBone Tree with Georgia Tech Source:** In order to assess the sensitivity of tree costs to source location we repeat the above analysis but assume a host at Georgia Tech is the source. The tree is changed to reflect the change in source, with the group members remaining the same.
3. **Internet Tree with Georgia Tech Source:** MBone hops are really tunnels which can span multiple Internet hops. In order to estimate the tree cost in terms of Internet hops we use the *traceroute*[12] utility and assume a host at Georgia Tech to be the source³. To the extent that the results from Item 2 above show little sensitivity to the location of the source, then these estimates should be close to what we would have obtained using paths from the true source.

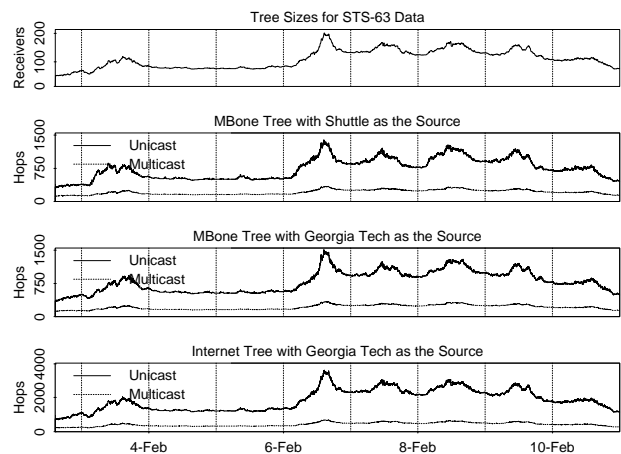


Figure 6. STS-63 multicast tree costs.

Figure 7 shows the tree costs for the STS-63 session. The results show that while there is a direct relationship between

³We are not aware of any technique that could have been used locally to determine Internet routes between two remote hosts.

the number of group members and the number of unicast packet-hops, the number of multicast packet-hops remains nearly flat. Even when the number of group members increases, the number of packet hops increases only slightly. The distance between source and the set of destinations averages 7.1 hops but the cost in the multicast tree is, on average, only 30.1% of the unicast cost. Changing the source for the STS-63 session does not significantly affect the tree cost or the average distance. Using the Internet topology, the results are similar but the Internet multicast tree is larger, containing 2.3 times more hops than the MBone tree.

Domain Breakdown. Additional analysis is conducted by grouping receivers based on their geographical location. Using a DNS server, a domain name can be determined for each receiver's IP address. Figure 7 shows a breakdown of the STS-63 session into three groups: (1) all hosts in North America, (2) all hosts connected to the MBone via trans-Atlantic links, and (3) all hosts connected via trans-Pacific links. Figure 7 shows that more than 50% of the receivers were in North America. The shuttle missions fall in the middle of the spectrum in terms of geographical distribution. Other, more general interest programs like the IMS World Radio Network have a much more even distribution while some programs are broadcast world-wide but have only local interest with respect to the source. A final observation is that activity in each of the three groups occurs during the day time hours but because each group is in a different part of the world, the daily activity is offset slightly.

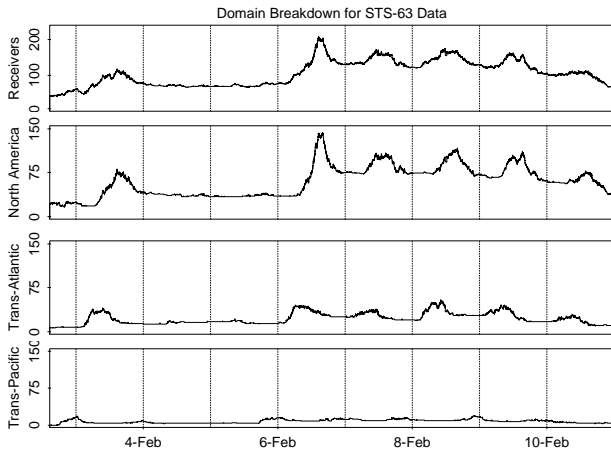


Figure 7. STS-63 domain breakdown.

5 Analysis of All Sessions

In this section we present an analysis of join/leave data collected from all active MBone audio sessions from February 26, 1996, to March 10, 1996 except for a 12 hour period

starting on March 6th. During this period, 60 million packets were collected. In addition to presenting temporal analysis results, we also present the results of a study on MBone user movement among active sessions.

5.1 Temporal Statistics

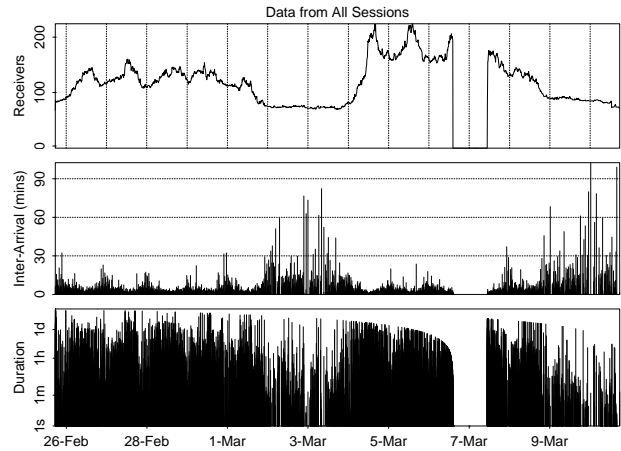


Figure 8. All sessions temporal statistics.

Figure 8 shows the temporal statistics for the all-session data. Some sessions have been removed including any encrypted, private sessions or test sessions. The removed sessions represent only an insignificant percentage of the total MBone. Table 1 shows the sessions that are included and some statistics for each.

The all-session statistics are generally similar to the statistics from the STS-63 session, and the STS-75 data is almost identical. What is most surprising is that two are so similar even though the data for each was collected more than a year apart. The all-session data is similar to other collected data in that most membership durations are very short but a few people in some of the sessions stay for a very long time. More than 75% of the membership durations are less than 10 minutes while the average is 2.5 hours. Finally, there are 8.9 group joins per host which is twice as many as the STS-63. This is due mostly to the fact that this data covers more than just one session.

5.2 Temporal Data Modeling

Figure 9 shows the results of an attempt to fit the all-session inter-arrival time and membership duration data. Our experience modeling this data is similar to work with the STS-63 data. An exponential distribution works well for the inter-arrival data and a Zipf distribution works well for the membership duration. Again, only a subset of the data

Session Names	Join Requests		Average Inter-Arrival	Average Duration
	Number	Percent		
NASA: STS-75	4230	27.55%	7.51 mins	4.3 hrs
IMS: World Radio Network	1998	13.01%	22.22 mins	1.7 hrs
IETF 1 - Audio	1343	8.75%	22.71 mins	2.6 hrs
IETF 2 - Audio	1234	8.04%	38.87 mins	2.4 hrs
Radio Free Vat	1179	7.68%	38.94 mins	49 mins
MBone Audio	839	5.46%	53.13 mins	4.4 hrs
FreeBSD Lounge	712	5.33%	67.57 mins	35 mins
Other IMS Sessions	1314	8.56%	56.00 mins	2.0 hrs
Short-Lived Sessions	2507	16.33%	18.11 mins	42 mins
Total	15356	100.0%	1.24 mins	2.5 hrs

Table 1. Statistical breakdown for all sessions.

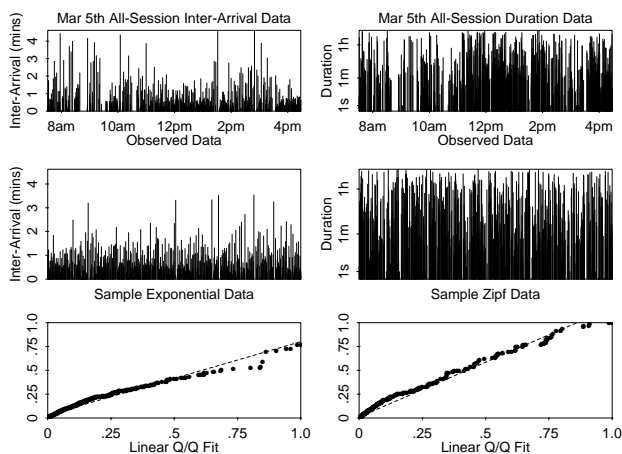


Figure 9. Fit of all session data.

can be modeled to these two distributions at a time because of daily and weekly variations in activity.

5.3 Inter-Session Statistics

Because we collect data for all sessions, we can analyze the behavior of users in multiple groups, and what they do when they leave a session. Using the log data we can determine if, within a time interval of two minutes, a user leaving one session either joins another session or becomes *inactive*. For the data presented in Figure 8, 70% of the hosts and more than 50% of all join actions occurred within two minutes of the host leaving a previous group. These results suggest “session surfing” is a typical behavior. Table 2 shows exactly where members leaving one group go. The rows represent the group that a member leaves from and the columns represent where the member goes.

Two interesting observations are (1) some sessions are

more tightly coupled and so see a much higher transition rate, i.e. IETF sessions, WRN and other IMS sessions, etc., and (2) sometimes users leave one group and within two minutes return to the same group; for example, 12.6% of STS-75 group members leave the STS-75 only to re-join it. This number is not a result of packet loss because the data has been processed. Likely reasons include accidentally closing then re-starting an audio tool, software crashes, or accidentally starting multiple instances of a tool and then quitting all but one.

In addition to inter-session transition statistics we have also analyzed information about users who run more than one session simultaneously. Because of hardware limitations, it is not possible to actually listen to multiple sessions at the same time but a user can still be a member of multiple groups. Results show that for the all-session data 45% of all hosts were members of more than one group at one time or another. 17% of all group memberships occurred when the host was already a member of another group. These results suggest simultaneous sessions occur, but not frequently,

6 Conclusions and Future Work

There has been a significant amount of work geared towards developing mechanisms to provide network support for multicast communication. The work reported in this paper complements these efforts by providing a tool that can be used to collect and analyze MBone multicast sessions. The tool, called *Mlisten*, collects the join/leave times for multicast group members in MBone audio sessions. Using data collected for a set of single MBone sessions and also data collected for all sessions we perform analysis to produce (1) basic statistics about group size and membership turnover, (2) information about the temporal and spatial dynamics of the multicast group, and (3) user join/leave behavior workloads and models. These results are extremely helpful in

To → From ↓	STS-75	World Radio Network	IETF Chan 1	IETF Chan 2	Radio Free Vat	MBone Audio	Free BSD	Other IMS	Other Sessions	Leave MBone
New	27.2	12.8	18.1	11.0	6.8	6.0	3.8	5.4	8.9	0.00
STS-75	12.6	6.2	6.0	2.8	5.1	2.2	1.8	2.9	2.6	58.2
WRN	8.9	12.9	3.3	2.2	6.2	4.0	2.4	7.9	4.0	48.2
IETF-1	4.0	2.1	10.6	37.2	1.3	1.3	0.9	1.9	1.0	39.8
IETF-2	5.8	2.3	21.3	14.5	0.8	0.9	0.8	1.9	0.5	51.2
RFV	6.5	11.8	2.5	1.8	8.1	7.3	2.1	4.8	6.7	48.6
MBone Aud	7.6	8.0	4.5	2.3	10.7	9.9	2.9	3.9	5.8	44.4
Free BSD	8.3	4.3	6.7	0.3	2.4	1.6	12.1	9.9	6.7	47.7
Other IMS	6.6	13.7	2.6	2.2	5.4	3.2	2.4	29.6	5.1	29.2
Others	3.7	5.4	1.1	0.9	3.6	2.2	7.4	4.7	22.1	49.0

Table 2. Entries represent the percentage of members leaving a session and joining another session.

understanding how multicast network support is being used and how it might be used in the future. Furthermore, the collected data is useful in the development and testing of efficient multicast routing and resource reservation algorithms and protocols.

7 Acknowledgments

This research was conducted with assistance from several people. Atanu Ghosh, University College London, provided help with the MWatch tool. Bill Fenner at Xerox PARC and Steve Casner at Precept Software explained some of the mysteries and anomalies in the MBone. Amarnath Mukherjee, Naser Adas, and Steve Klivansky at Georgia Tech offered help with data analysis and S-Plus.

References

- [1] D. Agarwal and S. Floyd. Tool for debugging internet multicast routing. In *22nd ACM Computer Science Conference*, Phoenix, AZ, Mar 1994.
- [2] K. Almeroth and M. Ammar. Characterization of MBone session dynamics: Developing and applying a measurement tool. Technical Report GIT-CC-95-22, Georgia Tech, Jun 1995.
- [3] S. Casner. *Frequently Asked Questions(FAQ) on the Multicast Backbone(MBone)*. USC Information Sciences Institute(ISI), Dec 1994. Available from <ftp://ftp.isi.edu/mbone/faq.txt>.
- [4] S. Casner and S. Deering. First IETF internet audiocast. *ACM Computer Communication Review*, pages 92–97, Jul 1992.
- [5] Y. Dalal and R. Metcalfe. Reverse path forwarding of broadcast packets. *Communications of the ACM*, pages 1040–1048, Dec 1978.
- [6] S. Deering, D. Estrin, D. Farinacci, V. Jacobson, G. Liu, L. Wei, P. Sharma, and A. Helmy. Protocol independent multicast sparse-mode (PIM-SM): Protocol specification. Technical Report draft-ietf-idmr-PIM-SM-spec-*.txt, IETF Internet Draft, Sep 1995.
- [7] S. Deering, A. Thyagarajan, S. Casner, and et al. *Mrouterd 3.5 and Tools*, Jun 1995. Available from <ftp://parcftp.xerox.com/pub/net-research/ipmulti/>.
- [8] S. E. Deering and D. R. Cheriton. Multicast routing in datagram internetworks and extended LANs. *ACM Transactions on Computer Systems*, 8(2):85–110, May 1990.
- [9] D. Estrin, D. Farinacci, V. Jacobson, G. Liu, L. Wei, P. Sharma, and A. Helmy. Protocol independent multicast dense-mode (PIM-DM): Protocol specification. Technical Report draft-ietf-idmr-PIM-DM-spec-*.txt, IETF Internet Draft, Jan 1996.
- [10] A. Ghosh and P. Brooks. *MWatch 3.6.2*. University College London, Jun 1994. Available from <http://www.cl.cam.ac.uk/mbone/index.html#Mrouterd>.
- [11] M. Handley. *SDR: Session Directory Tool*. University College London, Nov 1995. Available from <ftp://cs.ucl.ac.uk/mice/sdr/>.
- [12] V. Jacobson. *Traceroute*. Lawrence Berkeley Laboratory, Feb 1989. Available from <ftp://ee.lbl.gov/traceroute.tar.Z>.
- [13] V. Jacobson. *SD: Session Directory Tool*. Lawrence Berkeley Laboratory, Feb 1993. Available from <ftp://ee.lbl.gov/conferencing/sd/>.
- [14] V. Jacobson and S. McCanne. *VAT: Visual Audio Tool*. Lawrence Berkeley Laboratory, Feb 1992. Available from <ftp://ee.lbl.gov/conferencing/vat/>.
- [15] B. Mah. Measurements and observations of IP multicast traffic. Technical Report UCB/CSD-93-735, University of California at Berkeley, Mar 1993.
- [16] H. Schulzrinne. *Voice Communication Across the Internet: A Network Voice Terminal*. Department of Electrical Engineering, University of Massachusetts at Amherst, Jul 1992. Available from <ftp://gaia.cs.umass.edu/pub/hgschulz/nevot>.
- [17] G. Zipf. *Human Behavior and the Principle of Least Effort*. Addison-Wesley, Reading, MA, 1949.