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Design and implementation of a membership server and its application interface

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THESIS

DESIGN AND IMPLEMENTATION OF A MEMBERSHIP SERVER AND ITS APPLICATION INTERFACE

by

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March 10, 1995

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DESIGN AND IMPLEMENTATION OF A MEMBERSHIP SERVER AND ITS APPLICATION INTERFACE

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ABSTRACT

None of the existing membership protocols have all the properties needed to be reliable and fault-tolerant. Therefore, the goal of this work is to implement two major components of a group Membership Service protocol which will provide distributed applications the necessary fault tolerance, reliable communications and consistent group views among all members. These protocols must operate on top of a usually unreliable and best effort network such as the Internet. The first component implements a multicast emulator, to emulate IP multicasting communication over a mixture of multicast-capable and unicast capable local area networks (LANs). The second component implements a membership server that maintains the group memberships using the Membership Service protocol. These components are implemented as programs and then verified to be faithful to the specifications through extensive testing of all possible paths through the program (all combinations of scenarios).

TABLE OF CONTENTS

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This thesis is devoted to my father Dionisios Kostrivas for whom, higher education has been his life drive.

It is also devoted to all my professors and especially to my advisor Professor Shridhar Shukla, who helped me to materialize my dream.

I. INTRODUCTION

Distributed applications require co-operation among their groups spread out in a network. These groups sometimes change dynamically and the membership may be based on voluntary, as well as involuntary, actions. As such applications proliferate on a typical organization's wide area network (WAN), access to a Membership Service (MS) to manage and administer the membership information of individual groups becomes necessary.

The type of membership information required depends upon the nature of the cooperation to be achieved by the members of the client groups. Examples of membership-related information are group size, members' identities, their geographical and organizational distribution, and a history of membership changes. This information could be provided by the membership service through a series of functions that in turn could be used to build distributed applications.

A lot of different approaches have been presented [13, 14, 15, 16, 17, 9, 18, 19, 12, 20, 5, 21, 22, 23] for a membership service. None of them includes all the necessary features to provide total scalability over WANs. Typically, they do not provide a range of membership services and, in many cases, assume network properties that are not representative of today's WANs.

The MS described in [28] assumes a ``best-effort" network such as the Internet, is scalable with respect to the size/distribution/number of groups, uses network-level multicasting when available, employs a decentralized protocol with provably minimal number of phases for committing changes, and offers different qualities-of-service(QoS).

This thesis presents the algorithms and actual code of the MS implementation started in [28]. Two basic components of the MS, a multicast emulator (*mcaster*) and a membership server (*mserver*) were implemented and tested. In this process some of the membership protocols of [28] were refined. In Chapter II, a brief description of the MS architecture described in [28, 29] is given. The protocol is described in Chapter III. In Chapter IV, the implementation of the *mcaster* and *mserver* is explained. Chapter V gives the conclusions and future work. Finally, the Appendix describes how to compile, run and test the MS code written for this thesis.

II. THE ARCHITECTURE OF THE MEMBERSHIP SERVICE

The key to a scalable MS is a decentralized, hierarchical architecture, designed to exploit the existing physical topology of subnetworks, networks, and internetworks upon which the distributed application process groups that the MS supports will be running. This chapter summarizes the structure and composition of the physical hierarchy of the MS and how this architecture supports application process groups, as it is given in [28, 29].

A. COMPONENTS OF THE MS

1. Membership Servers And Member Interfaces

The MS is comprised of two primary entities: membership servers (*mservers*) organized in a physical tree hierarchy and member interfaces (MI) that represent the leaves of the tree. The *mservers* are primarily responsible for processing changes and providing information to the members of the physical hierarchy as well as the application process groups using the MS. Application group processes interface with the MS through an MI process running on each host computer. Each MI accepts requests for changes to or information about application groups from the individual application member processes running on the particular host computer. The MI then reliably relays these requests to the LAN *mserver* to access the MS. The MI receives responses from the LAN *mserver* and reliably propagates these responses to the application member processes that it supports. Each MI supports numerous application groups and numerous individual member processes from each application group.

Figure 1 illustrates an example logical hierarchy of *mservers*, MIs, and application group processes. The architecture shown is a representative configuration for a small area encompassing a single institution, such as a campus or business. The logical hierarchy shown in Figure 1 corresponds to the physical topology of networks and computers. It shows 11 departmental LANs served by as many *mservers*. The 11 *mservers* form 3 groups at the building level. At the next level (backbone) 3 *mservers* form a group to serve the entire campus. This hierarchy of *mserver* groups forms the MS infrastructure. Figure 2 shows the messages that are exchanged between LAN *mservers*, Member Interfaces and application group members.

The configuration of the *mservers* and MIs is expected to be semi-static, normally changing only when additions and deletions to the physical topology are made. The system administrator will assign appropriate names for each set of *mservers* at each level. If network-level multicasting is available, the administrator could join each set into a multicast group for efficient communication.

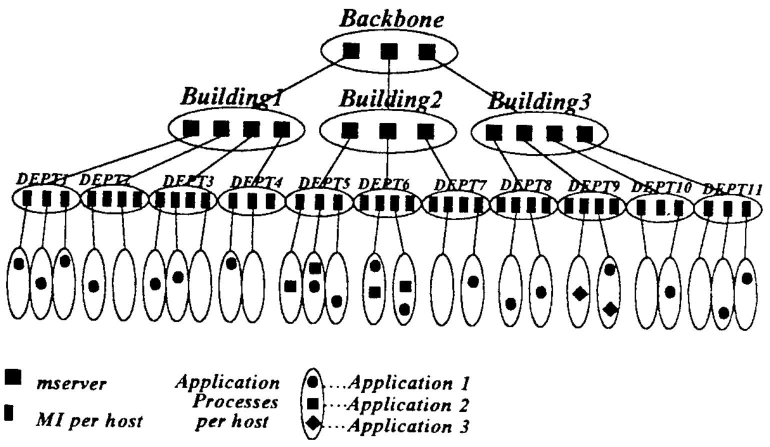


Figure 1: Logical MS Hierarchy

2. Failures, Partitions, And Dynamic Reformation

Mserver failures and network partitions lead to a dynamic reconfiguration of the physical structure of the MS, with the surviving *mservers* and MIs automatically reforming into partitioned sets. Perceived *mserver* failures represent virtual partitioning of the network into one or more subsets of the original set of *mservers*. Each partitioned subset corresponds to the subtree of the physical hierarchy in a single piece of the partition. This subtree corresponds to all of the *mservers* which are still able to communicate over the non-partitioned network. Each partition of the MS reforms and continues to function, providing service to all application process groups which have members still existing in the partition. The application process groups which span the partitioned network will experience a partition in their membership. This condition will continue until the physical network partition is repaired, at which time the physical hierarchy of *mservers* will either administratively or automatically be reformed to the original configuration. Once the physical hierarchy is restored, the surviving application groups will also be reformed, as per the Quality-of-Service (QoS) related to partition resolution chosen by the MS user at start up time. Partitions can be detected by mservers through monitoring, as described later.

3. Change-Processing Core-Set

The group of *mservers* at each level in the hierarchy is called a change-processing core-set with respect to a particular application group when it is designated to be responsible for processing all membership change requests submitted by members of that application group. Every such set is also responsible for enacting changes in the physical hierarchy immediately below it. The change processing involves reaching agreement amongst all *mservers* in the core-set about the change submitted and propagating this change back to the application or physical hierarchy group members, who are then guaranteed to have a new view of the changed group membership.

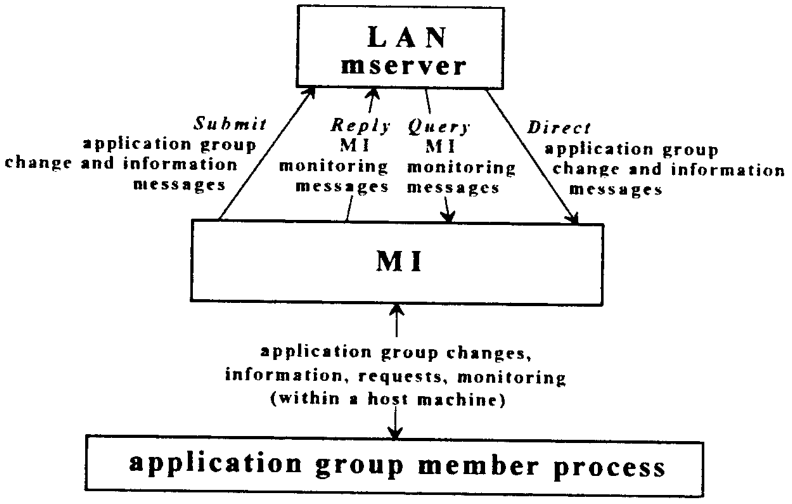

LAN mserver
Submit application group change and information messages
Reply MI monitoring messages
Query MI monitoring messages
Direct application group change and information messages
MI
application group changes, information, requests, monitoring (within a host machine)
application group member process

Figure 2: Messages sent by LAN Members and Member Interfaces

For each membership change request submitted to an *mserver* group, a coordinator is chosen. The criteria for selecting the coordinator depends on the particular type of change and how it was submitted to or detected by the *mserver* group. The fact that the coordinator is not a fixed member of the *mserver* group, but instead varies from change to change, is a powerful feature of the MS.

4. Lan *Mserver* Monitoring

Due to the high bandwidth, low latency, hardware multicast capability, and limited number of MIs to monitor, the *mserver* representing each LAN uses a simple polling scheme to conduct status monitoring of the MIs on the LAN. Each MI on the LAN is successively polled with a *Query* message by the LAN *mserver*. The MI responds with a *Reply* message indicating normal status. Timeouts and retries are used to detect a non-responding MI and announce the perceived failure. Note that this monitoring emphasizes collection of status of individual MI's on the LAN. This is to be distinguished from the monitoring done by IGMP which detects if there exists a (any) member on the LAN [6].

5. Forming The Hierarchy

The final organization of *mservers* and MIs involves forming the hierarchy of the sets of *mservers* that cooperate for monitoring and change processing, with the MIs at the leaf level. As shown in Figure 1, each *mserver* in the hierarchy has either a set of children *mservers* or MIs. All *mservers* and MIs also have a parent *mserver*, except the *mservers* at the highest level of the hierarchy. Each *mserver* above the lowest level in the hierarchy has a dual membership in the "child-set" as well as the original peer group of *mservers*.

Having the parent *mserver* as a member of the child-set has two primary advantages. First, the parent *mserver* is part of monitoring the child set; thus, the child-set will immediately learn of the failure of the parent *mserver* by monitoring. Second, the parent *mserver* takes part in all change processing conducted by the child-set; therefore, it will learn of any changes in the membership of the child-set directly. Together, these two points ensure that "vertical monitoring" is conducted in the hierarchy. This provides the means to ensure that a failure or partition between levels in the MS hierarchy will be detected, allowing the MS to reform as necessary.

B. SUPPORT FOR APPLICATION GROUPS

The MS is responsible for managing the membership of the application groups and providing services to the application groups with features as described below.

1. Consistency

The primary service that the MS provides application groups is a consistent view of the group membership at all members, as well as a consistent ordering of changes to the membership of the group at all members. These consistency guarantees ensure that a group member either acquires the same consistent view as all other members of the group eventually, or is excluded from the membership of the group. The term "eventually" refers to the asynchronous nature of the environment, leading to delays at some sites. Using this guarantee of consistent membership at all members, the application can expect that members with the same group view number have seen the same sequence of membership changes and have the same view of the membership of the group. Using this knowledge, the application can decide to accept or reject messages from other application processes depending on the included group view number [11, 27]. The guarantee of consistent membership can be used as the foundation upon which to build many distributed applications.

The MS provides consistent ordering of membership changes to application groups by ensuring that only one change is ever processed at a time in the core-set of that application group, and that all active member processes eventually receive this change. The selected change is committed by all core-set *mservers*, then reliably propagated to the MIs, and finally, to the distributed application member processes. The MS provides the guarantee that an application member process either receives each revised group view or is detected as failed, and excluded from the group. In this manner, all surviving application member processes are guaranteed to have exactly the same ordering of membership changes.

2. Naming

The MS manages the names of all application groups using the MS. Application group names are guaranteed unique within a predetermined scope. When an application group is created, the software call from the application to the MS includes as a parameter a level in the MS physical hierarchy, under which the application group name will be guaranteed unique. This name-scope parameter is either the actual name of the core-set or a level number above the MI level in the physical hierarchy. For example, to guarantee an application group name of "application1" as unique under the scope of the *backbone* core-set from Figure 1, the name *backbone* or the level number 2 would be used as the name-scope parameter. The name-scope level must be at or above the core-set level for the application.

With the creation of each new application group, the name-scope parameter is checked at each level in the *mserver* hierarchy up to and including the name-scope level. If the name already exists, the creation of the new group is refused, and an error code is returned to the calling application. If the name is not found, then it is registered at the name-scope level of *mservers* and a successful group creation is reported to the calling application. When new application members at distributed locations wish to join an existing application group, a join request is submitted via the resident MI, then propagated up the hierarchy until either an *mserver* is located with the application name stored or the highest level in the physical hierarchy is reached and the application name is not located. If the desired application group name is located, the new member is joined into the application group through the normal change-processing sequence, and a successful join is reported back to the requesting process. If the name is not located, an unsuccessful join attempt is reported back. Through judicious use of the name-scope parameter, application names may be used freely with little concern about duplicate name usage.

3. Membership Scope Control

An additional feature provided by the MS is the ability for an application to decide at what level in the MS physical hierarchy to limit the scope of the application group. By providing a membership-scope parameter with the creation call for a new application group, the application guarantees that the span of the application's membership will not exceed that of the given core-set level in the physical hierarchy. In return, the MS is able to provide more efficient service by limiting the scope of application group name searches to the membership-scope level and below. Instead of propagating every unsuccessful application group name search to the highest level of the MS hierarchy, the name search will cease at the membership-scope level. Without use of the membership-scope, it might be possible for a bottleneck to form at the "top" of the MS hierarchy.

4. Member Interfaces

The MI's accept application membership change and information requests from application processes and submit these changes to the *mserver* hierarchy for processing. When the change or information data is returned, the MI passes the data to the requesting member processes.

The MI, running on an individual host computer is capable of interfacing multiple application groups, each with multiple members, with the LAN *mserver* and maintains a list of all application groups it is managing as well as all member processes from these groups running on the host computer. Thus, the membership information for each application group is maintained in a decentralized, scalable manner. When an application member process needs to communicate with another application member process on a different host, it submits a request for addressing information to the MI. The MI relays this information request to the MS, which obtains the desired information from the MI managing the desired member process, and relays the information back to the requesting MI and application member process.

5. Application Group Change Processing

As previously discussed, application group change processing begins with the submission of a change request to the host MI. This request is relayed to the core-set of the application, which conducts the *mserver* change-processing procedure, resulting in all core-set *mservers* committing the change. Each core-set *mserver* then reliably relays the change directive down the hierarchy to the MI, and then to the requesting application process. Timeouts and retries are again used to detect failures and partitions.

In this chapter the architecture of the MS was briefly discussed and its components (*mservers* and MIs) along with the MS support for the applications were described. The next chapter describes the MS protocol.

III. PROTOCOL DESCRIPTIONS

This chapter describes in brief the protocol used in MS. More detailed analysis of the MS protocol along with correctness arguments can be found in [28, 29].

A. PROTOCOL FUNCTIONS

As described in [28], the basic change-processing protocol uses a modified form of the three-way handshake often seen in unreliable networks for reliable message delivery. The coordinator initiates the change processing with a multicast to all group *mservers*, collects acknowledgment (ACK) messages from all, then multicasts a final message for all to commit the change. Timeouts and retries are used by *mservers* waiting to receive *ACK*s or *Commit* messages from other *mservers* to ensure that continual progress is made toward completion of the change. As with the monitoring scheme, if the expected reply is not received from an *mserver* after the timeout period and all successive retries, then that *mserver* is declared failed and the failure is announced to all other *mservers* in the group.

The use of timeouts and retries on change-processing messages creates a secondary but essential method of detecting *mserver* failures. Since *mserver* monitoring uses unicast messages and change-processing uses multicasts, it is possible that a network partition could occur that affected only multicast message delivery between one or more *mservers*. The inability of *mservers* to communicate all necessary data creates a virtual partition between the *mservers*. Without the use of this secondary detection method, it is possible that one or more *mservers* could be functioning perfectly well, sending the required monitoring messages, but unable to respond to change-processing messages, thus creating a deadlock situation. The timeout and retries on change-processing messages ensures that an *mserver* unable to communicate will be detected failed, and the remaining *mservers* will be able to complete the change in a timely manner. In the event of a coordinator failure during the change processing, a distributed election is conducted and a new coordinator is elected to continue the original change. This is described later.

1. Types Of Changes

There are three primary types of membership changes processed by a group of *mservers*: requests, failures, and dynamic reconfigurations.

a. Requests

Requests are voluntary, planned membership changes, submitted to the group for processing by an application process or system administrator. Change requests for the MS physical hierarchy may be to *Join* to a *mserver* group, *Leave* a *mserver* group, *Split* a *mserver* group to form two new ones, *Merge* two *mserver* groups to form one, *Add_parent* to add a parent *mserver* to the *mserver* group and *Del_parent* to remove a parent from the *mserver* group. Physical change requests are multicast to a specific group in the hierarchy by a system configuration call, usually invoked by a system administrator during manual configuration of the MS hierarchy. Application group change requests are submitted to the resident MI process on the host computer by the application user. The MI then propagates the request to the group *mserver* above it in the hierarchy. The receiving group *mserver* queues the request to be processed when other higher priority changes have completed processing.

b. Failures

The second primary type of membership changes are detected failures. These detected failures may be the result of the actual failure of an *mserver*, MI, or application process, or the host machines upon which they are running. Additionally, network partitions will be perceived as failures of the partitioned *mservers*, and will lead to the processing of failures and reformation of the partitioned subsets of *mservers* and subgroups of application processes. The partitioning of the MS physical hierarchy leads to a partitioning of the application groups residing on this hierarchy. The MS automatically reforms both the physical hierarchy and the supported application groups in the event of a network partition. Failures detected or received by a group *mserver* are queued and processed according to their priority. Multiple failures queued at a group *mserver* are processed all at once, in a "batched" manner. This greatly reduces the time required to reform physical *mserver* groups or application groups.

c. *Dynamic Reconfigurations*

The final type of changes are the result of automatic actions taken by *mserver* groups. This type of dynamic reconfiguration occurs when new members join an application group, causing the span of the application group to increase beyond that presently covered by the current application core-set. In this event, the application core-set must be moved from the present level in the physical hierarchy to a higher level covering the new span of the application. This new level must be at or below the name-scope and membership-scope levels of the application group, if these levels were designated when the application group was created. The MS automatically moves the application core-set to the new level. In a similar manner, the departure of application member processes may lead to a reduced span of the application. An application core-set must have at least two *mservers* with application members in their subtrees; otherwise, there is no need to have the application core-set at this level in the hierarchy. If the application core-set is reduced to only one *mserver* supporting an application, the application core-set will automatically move down to the child-set of this *mserver*.

The repositioning of an application core-set is initiated by the set of *mservers* detecting the need to move the application core-set. Messages are exchanged between the old and new core-sets and a change involving the join or departure of the instigating application member is processed along with the change in application core-set level by both core-sets. After committing the changes, the internal state of all *mservers* in both core-sets is changed to reflect the new application core-set level.

2. Ordering And Priority Of Change Processing

A key issue associated with processing membership changes is the ordering of changes committed by the *mserver* group. As previously described, to guarantee consistent ordering of membership changes at all *mservers* in the group, only one change may be committed at a time. However, it is possible that more than one membership change may be submitted to or detected by the group at one time. Each receiving or detecting *mserver* in the group will attempt to become the group coordinator and initiate the change it received or detected. These multiple change initiation attempts are referred to as "virtually simultaneous", since they have all been initiated before the group has reached a consistent and uniform decision on the current change to process.

To resolve these virtually simultaneous changes and select only one change to be processed, a priority scheme is used. This scheme uses the type of change and the unique group id (rank) of the subject of the change to decide which change will be processed by the group. The subject of a change refers to the member whose membership status has changed. The highest priority is given to any current change being processed by the group; that is, a change which is in progress at an *mserver* (i.e. an *ack* to the *initiate* has been sent). It is essential that such a change progresses to completion at all group *mservers*; otherwise, the possibility of inconsistent membership views exists if some *mservers* commit the change while others do not. The next lower priority is that physical hierarchy changes always have priority over application group changes. This is because it is important to ensure a complete and whole MS infrastructure before attempting to change the membership of an application group using the MS. Once these decisions have been made, the priority of the change is determined by the rank or age of the subject of the change in the group. The only exceptions to this rule are for the failure of the coordinator of the current change or a *Join*. The failure of the coordinator of a change in progress, has priority over otherwise equal status changes. A newly joining *mserver* or member will not have an associated rank until after the join is completed. For this reason, the network address of the joining member is used instead of a rank number to decide priority among *Joins*. The final rule used to determine the priority of virtually simultaneous changes is applicable when changes are submitted to the core-set by different application groups with identical subject rankings in each group. In this case, a tie-breaker is needed, and the ranks of the coordinators in the group are used to decide which change will be processed. Various scenarios with respect to virtually simultaneous changes are described in [29].

B. CHANGE PROTOCOL

The basic change-processing protocol consists of two phases: the Initiate and Commit phases. A timeline for this protocol is shown in Figure 3. In the Initiate phase, the coordinator multicasts an *Initiate* message to all *mservers* in the group. The group *mservers* respond with *ACKs*, acknowledging reception of the *Initiate* message. When the coordinator has received all the acknowledgments, the second phase of the protocol begins with the coordinator sending the *Commit* message. This message indicates to members of the group that it is safe to commit the change. Phase I is achieved through a reliable schema. The coordinator sends the *Initiate* message a predetermined number of times if one or more group *mservers* do not reply. After that, it assumes that the *mserver*(s) that did not reply has (have) failed.

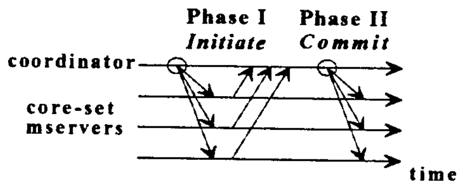


Figure 3: Basic Two Phase Change Protocol

C. CHANGE PROTOCOL WHEN COORDINATOR FAILS

The two phase protocol is not sufficient in case coordinator of a change fails while processing a change. As shown by Riccardi and Birman [9], a three phase protocol is required. After the coordinator of the current change fails, and its failure is detected by a member of the group, a three phase protocol is initiated, with the election of the new coordinator as the first phase. Figure 4(a) illustrates the three phase election and change processing protocol. In the election phase only those members that have finished phase one of the original change protocol participate.

When the new coordinator is elected, it knows the status of each member with respect to the change, due to a status broadcast during the election phase. If at least one *mserver* has finished the change (committed) it means that the old (and detected failed) coordinator had already collected all *ACKs* and had started the *Commit* phase. So the new coordinator, knowing that phase one was completed, can continue with the final phase of the change, instead of restarting phase one. This compressed three phase protocol is shown in Figure 4(b).

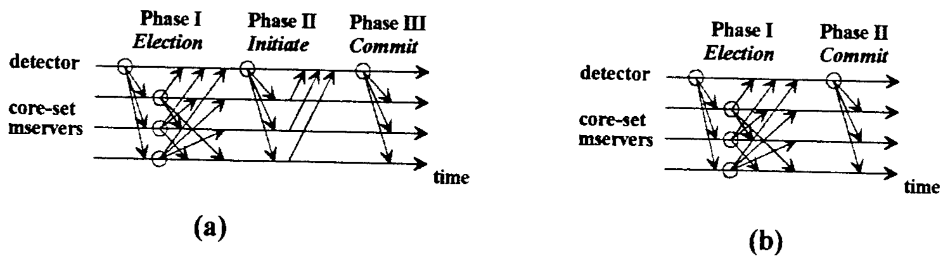


Figure 4: Three Phase (Election and Change) and Compressed Three Phase Protocol

A simplified algorithm for the two phase and three phase algorithm is shown in Figure 5. Only the important arguments are shown. All sends and receives of messages are done with timeouts. This way the protocol does not block and takes appropriate actions in case of no response. In line 5, the term "reliably" implies that a message is sent and specific answers are expected from all members in a specific time interval. If some or all of them do not reply, a number of retries are attempted. After the retries and the last timeout expire, the sender assumes the non responding *mservers* to have failed. In line 11, the same function is called recursively to process the failure(s) of the member(s) that did not reply. In line 8, the second phase is executed by sending a commit message. Then the coordinator has to make the change to its internal state. Lines 13 through 25 are devoted to the non coordinator. Since this code is executed everywhere, it contains both cases (coordinator, non-coordinator), and the if statement in line 3 decides which part of the code should execute.

Lines 17 through 25 form the three phase protocol in case the coordinator of the current change fails. Lines 17 through 21 refer to the member(s) that detected the failure of the current coordinator. Lines 22 through 25 refer to the member(s) that have still not detected the coordinator's failure but wait for a *Commit* message. Both sides triggered by the *coord_fail* message, start collecting status of the rest of the members. Then in lines 20 and 24 an election of a new coordinator is done. The lowest rank among the survived and responded *mservers* gets elected and all members go to process the new (and of higher priority) change. If the current coordinator does not fail, all members commit the change, updating their internal state, in line 27.

```
1. /*membeship change protocol */
2. process_change (type of change, subject)
3.      if coordinator
4.           /* start phase I */
5.           send agree to group reliably
6.           receive acks
7.           put members that did not reply, on fail list
8.           send commit message
9.           commit the change
10.          if fail list is not empty
11.               process_change (fail, first in fail list)
12.
13.     else /* non -coordinator */
14.          receive agree msg
15.          send ack to coordinator
16.          wait for commit
17.          if commit is not received
18.               send coord_fail msg broadcasting status
19.               collect status from other members
20.               determine new coordinator
21.               process_change (fail, old coordinator)
22.          else if coord fail msg is received
23.               broadcast own status and collect status from other members
24.               determine new coordinator
25.               process_change (fail, old coordinator)
26.          else /* commit received */
27.               commit change
```

Figure 5: The Membership Change Protocol (two phase - three phase)

D. PARTITION RESOLUTION PROTOCOL

After a network partition, it is possible that a group is partitioned into two or more subsets. This should happen as some of the group members see at the others as failed and proceed with the processing of these failures. Once the processing of the failures is completed these subgroups will attempt to rejoin once they learn about the existence of other subgroups. Since the subgroups still share the same multicast address, once the network partition is mended, all subgroups receive all the messages from the other subgroups. Upon learning of the existence of a subgroup from the original group, the partitioned subsets of *mservers* reform into the original group automatically by sending the appropriate reform messages. In addition to reforming the physical group, all application groups which were partitioned and are still functioning are also reformed. The reformation process for both physical subgroups and application groups merges the currently existing membership of each, taking the union of all subsets or subgroups, and making the reformed group or application group membership the current view. In the event that the network partition is not repaired in a predetermined period of time, the partitioned subsets of *mservers* will abandon their attempts to reform the original group, and will create a new multicast group with only the current group *mserver* included.

If the group partitions, the application groups that span the partition, also experience a virtual partition. These partitions are handled using the following two rules.

- Keep alive any partitioned subgroups that meet a certain condition specified by the user. Any subgroups which do not meet the condition are terminated.
- Partitioned subgroups attempt to find and merge with other partitioned subgroups that have a certain user-specified property.

By combining these two rules, every possible combination of partition handling methods can be produced. The first rule determines who survives, and the second rule determines who will attempt to merge. Each rule can also combine multiple parameters to provide very specific and flexible methods of handling partitions. For example, all subgroups larger than a size of three which contain a particular member type could be permitted to survive and merge with subgroups larger than half of the original group size and containing another particular member type. Note that all partitions of the group necessarily survive network partitions.

In the event that the partitions of *mservers* are unable to restore communications, the reformed subsets are converted to completely independent subgroups. Since all subgroups of *mservers* must have a unique name and multicast address, some method must be used to automatically obtain these unique values. To obtain a unique name, each subgroup appends a unique suffix to the original group name. This suffix value must be automatically derived by each partitioned subset of *mservers* independently, and with a guaranteed unique value for all partitioned subsets. The most readily available attribute that all subsets can use to obtain a guaranteed unique name is the original group identity (gid) of a significant *mserver* remaining in each partition. The lowest *mserver* gid of the *mservers* remaining in each partition is appended to the original group name. In this manner, all partitioned subgroups are guaranteed a unique group name. However, all partitioned subgroups are still easily identifiable as subsets of the original group, which simplifies the task of manually re-configuring the physical hierarchy when the network is repaired. Once a unique name is obtained, traffic on the same multicast address can be easily filtered by the individual subgroups.

This chapter focused on the MS protocol and its various aspects. The next chapter describes the implementation of two major MS components *mcaster* and *mserver* and how some of the features of the MS protocol were embedded into the latter.

IV. IMPLEMENTATION

This chapter describes the actual implementation of some parts of the MS protocol. As mentioned in the two previous chapters, the MS uses multicast to send and receive group messages. Since IP multicasting [30] may not be available at all LANs participating in the MS, there is a need for a multicast emulator that enables running the MS protocol over unicast-capable as well as multicast-capable networks and hosts. So the first step was the implementation of this multicast emulator, refered to hereafter as ***mcaster***. The next step is to implement an ***mserver*** capable at least of creating and maintaining an *mserver* group to be used as a *mserver* group, handling monitoring and some basic change requests. This is expected to enable the implementer(s) to start working on an application interface and create initial test applications. *Mcaster* and *mserver* programs are described next.

The terms "unicast-capable" and "multicast-capable" state the capability of a host or LAN to propagate group messages by sending them point-to-point or multicasting them respectively. The acronyms "uc" and "mc" will be used here.

A. MULTICAST EMULATOR (*MCASTER)*

1. Algorithm Design

IP multicasting requires that the IP multicast Extensions (1.2 Release) as specified in [30] are installed. Without these extensions, the MS cannot use multicasting to propagate messages to specified groups. *Mcaster* is an underlying program that enables the MS to virtually use the properties of multicasting in a uc environment with minimum overhead. If all LANs in which the MS runs are mc, the *mcaster* is not needed.

Mcaster must be able to listen to all multicast messages in the network and decide according to membership of groups which of them to propagate through the unicast channels. To achieve this, *mcaster* must be a member of all the *mserver* groups created. Since some members of an *mserver* group may have multicast capability while others may not, *mcaster* must maintain links for both unicast and multicast LANs. The administrator must foresee if there is any possibility of a mc host to become a member of the *mserver* group and place the *mcaster* process on the LAN that supports multicasting. This is an easy decision since one *mserver* will run per LAN. A typical scenario that includes both types of LANs is presented in Figure 6. If on the other hand, there are no mc LANs involved, *mcaster* must be able to run, simulating fully the multicast capability by repetitive unicast message transmissions. This is the first restriction that comes with the use of *mcaster*. The second comes with the use of extended header that messages, propagated through *mcaster*, have. As described by Neely [29], this is essential so that the final receiver of the message can extract the information about the original sender. Each time an *mserver* receives a message with a sender's address the same as the *mcaster*'s (which is known to all *mservers*), it tries to extract an extended header from it. This fact prohibits the MS from using the host that *mcaster* is running on, as the host that will run the *mserver* routine for the LAN that it belongs to.

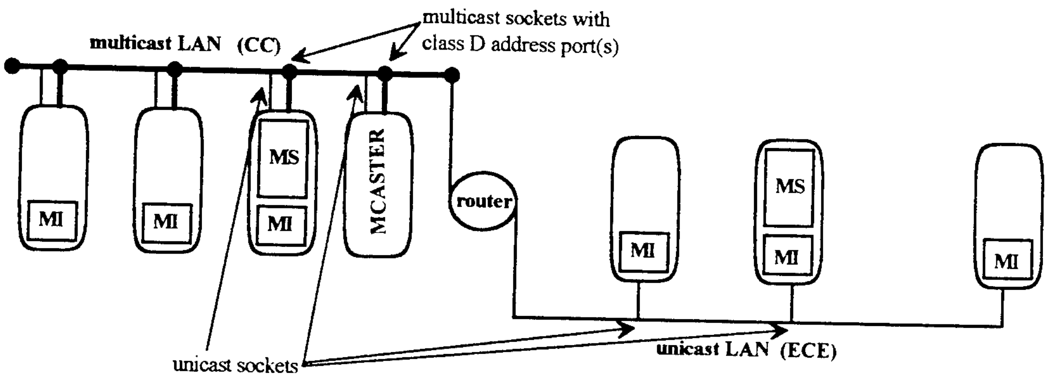


Figure 6: Typical *mcaster* communication diagram

Figure 7 describes the algorithm for *mcaster*, demonstrating its capability of detecting the type of LAN it runs on. In case of multicast LAN, it initializes a second socket to be used for multicasting to mc members. There are two types of messages that arrive at *mcaster*: those that are going for other members of the group, and those that are for the *mcaster* specifically. These messages can be either a JOIN_GROUP or a

LEAVE_GROUP and must be transmitted from any *mserver* that needs to join or leave a group. These two messages simply register and de-register the *mserver* with the *mcaster*. A JOIN_GROUP must be sent before an *mserver* sends any messages to the *mservers* in the group. These messages are the third restriction of using *mcaster*, and are essential for the *mcaster* to be able to maintain its local group lists and memberships for these groups.

In summary, the restrictions placed by the use of *mcaster* in the MS are:

1. Multicast is simulated at on uc LANs by repetitive unicast transmissions by *mcaster*. Therefore, *mservers* running on unicast LANs must have a unicast socket to listen to "multicast" group messages.
2. Since every message delivered by IGMP carries the address of the host that sent it, every message propagated by *mcaster*, has *mcaster*'s address. To be able to identify the original sender an additional header must be put on the message containing the address. This is done by *mcaster*. Receivers must identify if the message comes from *mcaster*, to extract this additional header.
3. Each member of the group must register itself into *mcaster*'s internal list of groups. This is essential for the operation of *mcaster*. Therefore, each new member must join *mcaster*'s internal group, before attempting to join the real *mserver* group. Leaving the *mcaster*'s internal group after leaving the real *mserver* group is not essential, unless the same host is going to be used for a new copy of an *mserver*.

Every *mserver* that needs to join or create a group, sends initially a JOIN_GROUP to *mcaster*. Lines 9 through 17 show how this message is used by *mcaster* to maintain updated group lists. If the group needs to be created, *mcaster* does so, and then if it runs on a mc LAN, it actually joins IP multicast group specified by the class D address, even if the original sender is a uc *mserver*. This reserves the class D address group in the mc LAN for future mc *mservers*.

Line 25 is the most vital to *mcaster*'s functionality. It is shown here as a call to a function, *mcast*. If a message is not sent for the *mcaster* specifically (i.e. JOIN_GROUP or LEAVE_GROUP) then it is propagated to the group it was sent for. Figure 8 shows the algorithm for function *mcast*. *Mcaster* extracts the group information from the message header, uses this information to locate the group in its own internal list, then adds the additional header that will enable the final receiver to extract the sender's information. Finally, it sends out zero or more messages, according to the logic shown in Figure 8, so that the message will reach every member of that group.

```
1. /* MCASTER */
2. Initialize first (ms) socket              /* this socket is used for unicast communication */
3. Initialize second (mc) socket             /* this socket is used for multicast communication */
4. if on a multicast (mc) lan, then
5.        use mc socket for multicast communication
6. else
7.        mc socket is not used
8. for every message
9.        if msg_type = JOIN_GROUP
10.              if group exists
11.                     join member to group
12.              else
13.                     create group
14.                     join member to group
15.                     if mcaster on a mc LAN
16.                            join mcaster to group
17.              send reply to sender
18.       else if msg_type = LEAVE_GROUP
19.              if group exists and member of this group
20.                     delete member from group
21.                     if group becomes empty
22.                            delete group
23.                            mcaster leaves class D address port
24.       else                            /* must send message to members*/
25.              mcast message to group members
26. end for
```

Figure 7: Algorithm for Multicast Emulator (*mcaster*)

A group may have both uc and mc members. Also, the sender can be either uc or mc. Since mc member communication is taken care of in the IP mulitcast level, if the sender is mc, there is no need for *mcaster* to reroute the message to the same class D address (address of a multicast group). That is why after line 15 in Figure 8 there is no if statement for the mc members. For the same reason, if the sender is uc, and one member is found to be mc, then *mcflag* ensures that only one message will be transmitted to this class D address. For all uc members in a group, a per member peer-to-peer transmission of the message must be used, so that the message arrives at all of them, as shown in lines 13 and 17.

```
/* function MCAST */
mcast (msg, sender)
    extract sender and group info from msg
    form extended header
    if group does not exist in list
        exit
    for each member in the list maintained by mcaster
        if sender is uc
            if this is mc member and mcflag = 0
                send msg to class D address for this mc member
                set mcflag = 1    /* no need to re send msg to mc socket */
            else if this is uc member
                send msg to uc member     /* through uc socket */
            go to next member in list
        else if sender is mc
            if this is uc member
                send msg to uc member     /* through uc socket */
            go to next member in list
```

Figure 8: Algorithm for the Message Propagation Function *mcast.*

2. Code Description

The *mcaster* code is very important for future work since the way it creates, maintains and updates internal state for the *mserver* groups is the same that will be used from MIs to maintain information about the application groups. In Figure 9 the initialization part of code for the *mcaster* is shown.

```
1.   /* test_addr will be used for testing the mc port */
2.   test_addr.s_addr = 0xe10f0f0f;
3.   /* Initialize sockets */
4.   ms = init_socket (&sin, MS_PORT);               /* unicast socket */
5.   print_sock_info (ms, sin);
6.   mc = init_socket(&mcsin, MC_PORT);              /* multicast socket */
7.   /* join a class D address to test mc capability */
8.   reply = join_mc_grp (mc, test_addr);
9.   if (reply == JOIN_ACK) {
10.      lan = 1;
11.      print_sock_info (mc, mcsin);
12.      leave_mc_grp (mc, test_addr);
13.  }
```

Figure 9: Initialization Code for *Mcaster*

In line 4 the unicast socket is initialized. To initialize a socket for multicast communication, *mcaster* must run on an mc host. To test if the host it runs is mc, it picks an arbitrary class D address in line 2 and tries to join a mc group for this address in line 8. If it succeeds, then flag variable *lan* is set to 1 in line 10 and *mcaster* leaves the class D address group in line 12.

After initialization of *mcaster* is finished, it starts listening to the port(s) for possible messages. Figure 10 shows the loop of waiting, receiving and processing messages of *mcaster*. Whenever it receives a message in line 2, it extracts the message type in line 3 and goes to appropriate actions according to line 4 switch statement. The first two cases are the *mcaster* specific types of messages and are used to inform the *mcaster* about a change in the group. This way *mcaster* keeps its lists updated. These two cases are explained later.

The default case is executed whenever an ordinary message is trying to propagate to the group. *Mcaster* calls function mcast to retransmit the message as explained earlier in the algorithm section.

```
1.    for ( ; ; ) {            /* wait for incoming messages */
2.        if ((sent = receive_msg (ms, mc, &ws, &m, &from, recv_timeout)) > 0) {
3.            message_type = ntohs(m->msg_type);          /* check type of received message */
4.            switch (message_type) {
5.                case JOIN_GROUP:
6.                . . .
7.                case LEAVE_GROUP:
8.                . . .
9.                default:
10.                   /* if sender is mc do not mcast to mc members */
11.                   all = ws ? 0 : 1;
12.                   mcast (ms, mc, m, from, all);
13.           } /* switch */     } /* if */     } /* for */
```

Figure 10: Main Waiting Loop of *Mcaster*

The operation of *mcast* function depends on whether *mcaster* runs on a mc LAN or not and whether there are both types (mc and uc) of members in the specified by the message group or not. When propagation of a message is finished, control is returned to main loop and *mcaster* waits for the next message to process.

a. *Internal Group Lists*

As mentioned above, *mcaster* keeps an internal list of *mserver* groups and lists of members for each group. These lists can change dynamically and are kept as linked lists. Figure 11 shows two structures defined in "msutil.h" header file, that are used as elements for the group linked list and for the members' linked list. A graphical representation of these lists can be found in Chapter VI of [29].

```
1. /* element in list of members */
2. struct member {
3.      struct in_addr     addr;
4.      u_char             lan;          /* lan = [0 if member on a unicast, 1 if on a multicast lan] */
5.      u_char             loop;
6.      struct member      *next;
7. };
8. /* element in list of groups */
9. struct group {
10.     char               name[MAXGROUPNAME];      /* name of the group */
11.     struct in_addr     grp_addr;                /* classD grp address */
12.     struct group       *next;
13.     struct member      *members;                /* first member */
14.     struct member      *last;                   /* last member */
15. };
```

Figure 11: Structure Definitions for Members' and Groups' Internal Lists of *Mcaster*

A whole series of function calls was implemented to support proper searching, adding and deleting members and groups from these lists. All these functions are inlcuded in the "*mcaster*.c" file, with a comprehensive description of their arguments and functionality.

b. Mcaster Specific Messages

As mentioned before, two messages that are specifically for the *mcaster* are: JOIN_GROUP and LEAVE_GROUP. Both of them have the standard message format used throughout the MS code, with the latter carrying an empty data section. JOIN_GROUP, in its data section, has a copy of a short integer, showing whether the sender of the message is mc or uc (as described in Figure 11 line 4). This is essential so that *mcaster* maintains a complete image of each member. Also, function *mcast* uses this field to avoid sending out unnecessary messages.

Mcaster replies to the above messages according to its internal state. Figure 12 summarizes the definitions of these types of messages as they are found in "msutil.h" header file.

Each of these messages, exchanged between *mservers*, who try to change their membership to *mserver* groups and *mcaster*, does not use the extended header format. To receive such messages, function *receive_msg* is used. All other messages, when received by *mservers*, have the possibility that they were propagated through *mcaster*. In such a case the message has an extended header and the receiver must check the sender's address. If it is the same as the *mcaster*'s, it extracts from the extended header the address of the original sender. The function that makes such a discrimination is *recv_messg*. Both these receiving functions along with basic forming and sending message functions have their definitions in "msutil.h" header file and the code in the "msutil.c" utility file. An outline of these functions follows in the next section.

```
/* mcaster related message types */
#define JOIN_GROUP      120    /* request to join a group list kept by mcaster */
#define LEAVE_GROUP     121    /* request to leave a group list kept by mcaster */
#define JOIN_ACK        130    /* mcaster positive reply to JOIN_GROUP  */
#define DUP_MEMBER      131    /* mcaster negative reply to JOIN_GROUP; member found in list */
#define NEG_JOIN        132    /* mcaster negative reply to JOIN_GROUP; problem with port */
#define LEAVE_ACK       140    /* mcaster positive reply to LEAVE_GROUP */
#define NO_GROUP        141    /* mcsater could not loacte the group in its list */
#define NO_MEMBER       142    /* mcaster could not locate the member in the group's list */
#define NEG_LEAVE       143    /* mcaster negative reply to LEAVE_GROUP */
#define GROUP_EXISTS    150    /* mcaster found the group requested in its list */
```

Figure 12: Definitions for *Mcaster*'s Related Types of Message.

B. BASIC MESSAGE FUNCTIONS

1. Function Receive_Msg

Function *receive_msg* receives a message from the buffer of a port and stores it into a variable. Since the multicast emulator and membership server (*mserver*) have at most two sockets, one each for unicast and multicast, the first attribute of function *receive_msg* is to be able to listen to both and receive from either of them whenever a message appears. Information about who sent the message and, of course, the message itself must be returned. Figure 13 lists the heart of the code for function *receive_msg* that actually monitors two ports for any incoming message and then uses the library function *recvfrom* to receive it.

```
1. int   receive_msg (ms, mc, w, msg, frm, timeout)
2. . . .
3.     FD_ZERO (&fdread);                          /* Initialize for reception from multiple sockets */
4.     FD_SET (ms, &fdread);                       /* Unicast socket */
5.     if (mc >= 0) FD_SET (mc, &fdread);          /* Multicast socket */
6.     if ((ready = select (32, &fdread, 0, 0, &timeout)) < 0) {    /* Wait until either socket is ready */
7.          perror ("Select error\n");   return -1;      }
8.     if (ready) {
9.          if (FD_ISSET (ms, &fdread)) {                     /* Unicast socket receives */
10.              *w = 0;
11.              if ((sent = recvfrom (ms, buf, MAXMSGLEN, 0, frm, &len)) < 0) {
12.                   perror ("Error in  UC message received\n");return -1;}
13.         } else
14.         if (mc >= 0)
15.              if (FD_ISSET (mc, &fdread)) {                /* Multicast socket receives */
16.                   *w = 1;
17.                   if ((sent = recvfrom (mc, buf, MAXMSGLEN, 0, frm, &len)) < 0) {
18.                        perror ("Error in  MC message received\n");     return -1;}
19.              } . . .
```

Figure 13: Function *receive_msg* Receives Messages from Two Sockets.

The first two arguments are the two socket numbers. If the calling program needs only one socket to read, it can set the second, *mc*, to -1. In line 5 this disables the second socket. Argument *w* returns 0 or 1 in correspondence with the socket that the message was read from. Argument *msg* returns a pointer to the message and argument *frm* a pointer to sender's address structure. Finally, the calling program defines a period of time during which a message maybe received using *timeout*. After time period expires and no messages received, *receive_msg* returns a NULL pointer. This makes the function non-blocking and gives the calling program the opportunity to regain control and decide what to do next even if no messages were received. Normally, the function is called with a small *timeout*, like one second, because messages are stacked in the ports, so that usually when the socket is read, the message is already there. *Receive_msg* is a blocking function and will wait for a message if the buffer of the port is empty until the *timeout* expires.

2. Function Recv_Messg

This function is similar to *receive_msg*, except it checks the sender's address against *mcaster's*. When a message is propagated through the *mcaster*, it arrives at the destination with an extended header, including the address of the original sender. If the receiver calls *receive_msg* to read these messages, it will return with *mcaster*'s address as the sender's address, since the C library functions [31] read what IGMP puts as a sender (and it is always the real sender - *mcaster* in this case).

Function *recv_messg*, shown in Figure 14, solves this problem by comparing *mcaster*'s address with sender's address and if the same, reads the extended header of the message and replaces the sender's address with the one in the header. It is obvious that this function cannot be used with messages listed in Figure 12. These messages are used to communicate between *mcaster* and *mservers* and do not contain an extended message header. The extended message header and its description can be found in [29, pages 102 - 103, Figure 53]. Function *mcast* of *mcaster* constructs and puts the extension to the message just before retransmitting it.

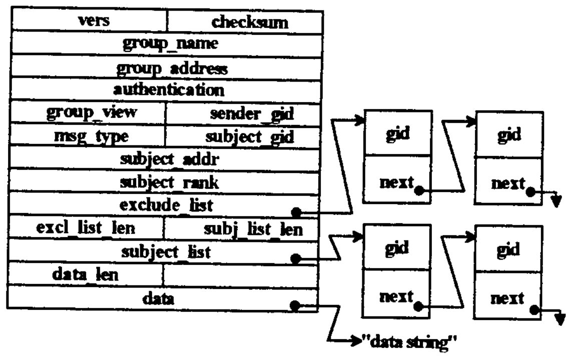
```
int recv_messg (ms, mc, w, mcstr, messg, from, timeout)
{     ...
      int   len = sizeof(struct sockaddr_in);
      ...
            /* check if sender is mcaster and if so, extract the original sender's address */
            if ((from->sin_addr).s_addr == mcstr.s_addr) {  /* message came from mcaster */
                  bzero ((char *)from, len);
                  bcopy (messgbuf, (char *)from, len);       /* copy original sender's address to "from" */
                  mp = messgbuf + len;                       /* set ptr to beginning of message */
            } else                                           /* message not from mcaster */
                  mp = messgbuf;
      ... }
```

Figure 14: Function *recv_messg* Extracts Sender's Address from Extended Message.

Recv_messg works as follows: it checks the sender's address against *mcaster*'s, which is passed as an argument, and if they match, it replaces the sender's address with the one that it finds in the first *len* bytes of the message (where the extended header is supposed to be). Since it uses the low level *bcopy* standard C function, if used to receive *mcaster* generated (not propagated) messages, it may lead to unexpected results, without necessarily showing an error like "core dumped".

3. Function Form_Messg

This is a relatively simple function. It takes as arguments all the components of a regular message, as described in [29, Chapter IV, Section B] and shown in Figure 15 and returns a pointer to a message structure. There is a deviation from the original message format: after the group_name field there is another field of type in_addr to hold the class D group address the message is going to. This was considered necessary as the tuple {group_name, group_address} defines a multicast group completely.



```
struct message {  /* to build and receive messages */
  u_short          vers;
  int              checksum;
  char             group_name[MAXGROUPNAME];
  struct in_addr   grp_addr;
  u_short          group_view;
  long             authentication;
  u_short          sender_gid;
  u_short          msg_type;
  u_short          subject_gid;
  struct  gid_entry    *exclude_list;
  u_short              excl_list_len;
  struct  gid_entry    *subject_list;
  u_short              subj_list_len;
  char                 *data;
  int                  data_len;
};
```

Figure 15: MS General Message Format and the Corresponding Data Structure

Pointers to exclude list, subject list and data along with the length of each field are also passed as arguments, so that the correct number of bytes is copied from each one. Finally, function *make_chksum* is called to evaluate the checksum field just before it is entered to the message structure. At this time, *make_chksum* is a dummy function, always returning a constant number.

4. Function Send_Messg

Function *send_messg* sends a message through a specified socket to the specified address. Its code was originally written by Neely [29] and was slightly modified to meet the changes described above. It copies the message, the exclude list, the subject list and the data to sequential bytes of a buffer and then calls the library function *sendto* to send that buffer to the socket port. The socket can be either a uc or an mc. The IP multicast extensions, described in [30], overload the library function *sendto*, making no difference wether the socket is uc or mc.

C. MEMBERSHIP SERVER (*MSERVER*)

1. Algorithm Design

The basic module in the MS is *mserver*. Each *mserver* process controls a whole LAN or subset of hosts on a LAN. *Mservers* join into *mserver* groups, monitoring each other and exchanging messages. Depending on the type of the LAN they run on, they use the multicast capability, or try to send messages to the group by a single transmission, using the multicast emulator, *mcaster*. Messages can be *mserver*-group specific or just received from the applications' Membership Interface processes, MIs.

Figure 16 shows the basic communication diagram of *mservers* through IP multicasting or through *mcaster*. Two cases are demonstrated: on the left, the sender is mc, on the right the sender is uc. The types and related names (as defined in "msutil.h" header file) of the sockets used are also shown in this figure. To send and receive group messages, uc *mservers* rely on the *mcaster*. Monitoring messages are sent and received through the designated unicast sockets. Finally, as described in the previous section, communication between *mserver* and *mcaster* is done through the unicast socket. In all cases, the format of the message is the same. Destination of a group message is defined by the tuple {group_address, group_name}. The group address is always a class D address. Although the group address is sufficient to specify a group, the group name is reserved for future features such as multiplexing of groups with different names on a single address. The algorithm for *mserver* consists mainly of three phases: the *initialization* phase, the *new member join* phase and the *basic monitor and process message loop* phase. The first two phases are executed once, when *mserver* comes to life. *Mserver* spends the rest of its life in a loop, monitoring its clockwise *mserver* in the *mserver* group (if it exists) and processing any messages read from its socket(s).

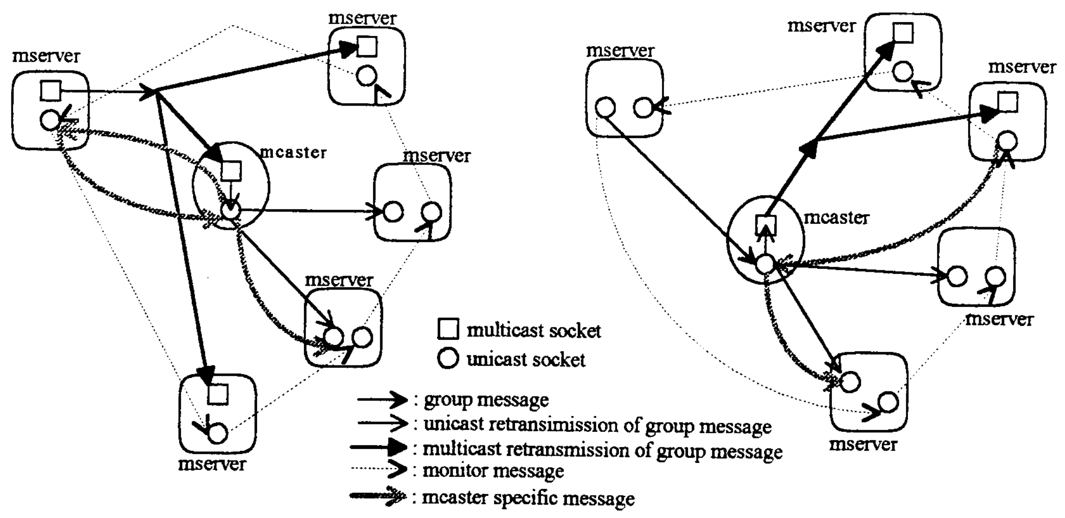


Figure 16: Communication Among *Mservers*

Figure 17 outlines the algorithm for *mserver*. As stated in line 3, some command line arguments are provided. A command line call to *mserver* looks like:

```
%> mserver grpaddr, grpname, mcasterIP
```

where **grpaddr** is the *mserver* group class D address selected by the system administrator, **grpname**[1] is a name for this group and **mcasterIP** is the IP address of the host on which the multicast emulator runs, provided in dot notation [31]. Next, sockets are initialized and finally *mserver* sends a message of type JOIN_GROUP to *mcaster*, whose address is known from the command line argument. The message to *mcaster* informs it about the *mserver*'s intention to join a group. If no reply is received, *mserver* assumes that there is no *mcaster* available on that address. If *mserver* runs on a multicast LAN it assumes that the system administrator plans to create a group of mc *mservers* only and continues normally. If it runs on a uc LAN, then without *mcaster* the MS exits, as it needs some form of multicasting. It also exits if a reply received from the *mcaster*, is other than of type JOIN_ACK, implying there is some kind of a problem.

[1] Up to 32 characters long or as specified by variable *MAXGROUPNAME*, global defined in "msutil.h" header file. *Grpname* must be enclosed in double quotes if it contains special characters like '&' or space(s).

```
1. /* MSERVER */
2. /* Initialization phase */
3. Read command line arguments
4. Initialize socket(s)
5. send_msg (JOIN_GROUP, mcaster)
6. wait reply for a timeout interval
7. if no reply is received                    /* mcaster is assumed not to be present */
8.      if mserver runs on a uc LAN
9.           exit              /* no mcaster and no IP multicasting; protocol cannot go on */
10.     else
11.     /* continue on a pure IP multicasting environment; no mcaster is available and no uc members may join later */
12. if received reply from mcaster is not JOIN_ACK
13.     exit
14. /* New member join */
15. join_group            /* creates the group, if it does not exist */
16. /* basic monitor and process message loop */
17. reset_timer (monitor)
18. do loop
19.     try to receive any msg from socket(s) in time period t_recv
20.     if no msgs received
21.          update internal state
22.          if timer(monitor) expired
23.               if there is a clockwise member in core table
24.                    reply = reliable_link(QUERY, REPLY, cw_member, T_R_QUERY)
25.                    if no reply received
26.                         add cw member to fail list
27.                    if reply = QUERY                 /* someone tries to monitor me */
28.                         goto 31;
29.               reset_timer (monitor)
30.     else if a msg was received
31.          if msg = QUERY
32.               send REPLY to sender
33.          else
34.               process_msg (msg, sender)
35. end loop
```

Figure 17: Algorithm for *Mserver*

If everything goes normally in the initialization phase, *mserver* in lines 9 and 10 tries to join the *mserver* group, as specified by its command line arguments *grpaddr* and *grpname*. If it succeeds, it enters the main loop, where three basic operations are executed: 1) receive and process messages, 2) monitor and 3) update of the internal state. Processing messages is done in function *process_msg* described later. To make the loop faster, monitoring takes place only when no messages are heard from the other members. If the *mserver* group is busy sending change messages, then one of the change protocols will discover the failures, if any. Thus, additional monitoring is not required.

The procedure of a new member joining a group as well as function *reliable_link* are explained in the next subsections. A description of the internal state of the *mserver*, part of which is the *fail_list*, is given in the next section.

a. New Member Joins Group

The procedure of joining the group is described in Figure 18. The logic is simple: it tries to communicate with the other members of the *mserver* group, sending a request for join. As given in the protocol description [29], normally the group will process the change through a 2-phase protocol, resulting in the second phase of the multicast of a COMMIT message. This message is received by the new member also. The procedure of sending a message, waiting for a specific reply for a certain time and retrying all over again in case of wrong or no reply, is done by the function *reliable_link*, discussed later.

After certain retries, *reliable_link* returns the message (if any) it read. The new member's actions depend on this answer, as described in lines 5 through 13. If no answer was received, in line 5 *mserver* assumes there is no group yet and initializes its own internal state in line 6. The internal state now contains the new group with the *mserver* as the only member.

```
1. /* join_group */
2. time = T_M_JOIN_REQ;                              /* set timeout variable */
3. do loop
4.      answer = reliable_link (M_JOIN_REQ, COMMIT, group, time)
5.      if no answer was received                    /* mserver is alone in this group */
6.           initialize internal state
7.           exit
8.      else if answer = COMMIT
9.           update internal state
10.          exit
11.     else                          /* answer was not the expected COMMIT */
12.          time = time * 6;            /* group members are busy; increase wait time by 6 (arbitrary) */
13. end loop
```

Figure 18: New Member Join Algorithm

If a COMMIT answer is received, then in line 9 the new *mserver* updates its internal state according to the contents of the COMMIT message. This message is transmitted by the group coordinator of the join change and contains the internal state updated to include the new member. The new member just copies this internal state to its own.

There is also the possibility that the new *mserver* receives as an answer a message other than COMMIT. In this case the group exists but probably other higher priority changes are being executed. If this is the case, the new *mserver* goes back to line 3 for a new round of reliable communication, but decides to wait a little longer than its previous attempt, as indicated in line 12.

b. Function Reliable_Link

This function is used to communicate by the sender that calls the function, with the specified receiver (or group) through a series of retries and timeouts to ensure reliable connection. The combination of sending a message to a specific member or group, waiting for a specific reply for a certain period of time and then trying all over again, up to specific number of retries, results in function *reliable_link*. Its algorithm is shown in Figure 19. It needs the message to be sent, the expected reply, the recipient and amount of time to wait for the reply (the number and specifications of arguments passed to the real function must not be misunderstood with the simplified explanation given here at algorithm level). The effect of this function is to make the sender attempt to establish a reliable connection or link with the receiver (member or group).

As shown in Figure 19, a message is received in line 6 using *recv_messg*. If it does not match the expected message type, it tries to receive a new message until timeout expires as controlled by line 5. Then it sends the original message again and resets the timer. The whole schema is repeated *max_retries* times. If at any time the expected message is received, the function returns with the reply at line 8. After the retries are exhausted, it returns with the last message read, at line 11. The return message can be null indicating no messages were received at all.

Unexpected messages are ignored while in the timeout loop. When timeout expires if an unexpected message is the last received, the function retries again by resetting the timer. This is repeated *max_retries* times. When last timeout expires and still the expected message is the not received, the last message received is returned. The caller has to check if this was the answer that it expected. If no message was received, a NULL message may be returned.

```
reliable_link (outmsg, expected_msg, recipient, timeout)
    max_retries = MAX_RETRIES, retries = 0
    while retries != max_retries
        send msg to recipient
        while timeout has not expired
            reply = recv_messg ()
            if reply = expected_msg
                return reply
        reset timeout
        retries = retries + 1
    return reply
```

Figure 19: Algorithm for Function *Reliable_link*

2. Internal State

Each *mserver* must keep internal information about its *mserver* group and real state of itself and other members. This internal state must be kept updated to reflect the most recent changes. The internal state of an *mserver*, at this level of implementation, can be described as the **core table**, the **fail list** and the **view**. These components are described here.

a. Core Table

Core table is an array of structures as shown in Figure 20. Under normal conditions, each member has the same copy of information in its own table. Each member is assigned a rank when joining and its information lies at the same line of the table. It may seem that *cw* and *ccw* fields are redundant, but they are useful during the processing of one or more changes, where ranks and the table itself are not updated yet.

```
struct table_entry {          /* member's entry in set table */
    u_long   addr;            /* IP address of member */
    u_short  rank;            /* rank (or gid) of member */
    u_short  cw;              /* gid of clockwise member (to "left") */
    u_short  ccw;             /* gid of counterclockwise member */
    u_char   flag;            /* status flag for each member */
};
    . . .
struct table_entry      cs_tbl [MAXTBLSIZE];
    . . .
```

Figure 20: Core Table Structure and Definition

b. View

View is an integer kept by each member of the group internally. When the group is idling with no changes being processed, *view* is the same in every *mserver* participating the group. *View* is incremented by one for every new change at the end of the change (commit phase). In this way, every change is marked uniquely by a number and can be identified with that number. *View* is used to put changes in sequence, give them priority or simply discard them because they came out of order, according to the state of the group and the members themselves. In normal conditions, *view* must be the same in every member of the *mserver* group.

3. Processing Messages - Function *Process_Msg*

This function is used to process any message according to the state of the caller and the type of the message. In *mserver*'s main loop of operation, the incoming messages get processed by *process_msg*. This function actually implements both the two-phase and the three-phase protocols. Moreover, it can be called recursively to handle more than one change in the order specified by the priority and the phase of each change. Figure 21 shows a simplified algorithm of *process_msg*.

The function is divided into two parts: The part that is executed by the coordinator and the part that is executed by all other members. In phase I, the coordinator sends the AGREE message through a reliable link similar to that provided by function *reliable_link*. The new function, *rel_mlink*, establishes reliable links with all members in a group. Then, a reply is expected by everybody. If a group member does not reply after *rel_mlink* returns, it places the non-responding member(s) on the fail list to be processed later.

When AGREE is sent out by the coordinator, *process_msg* gets activated in the non-coordinators, resulting in their sending back the AGREE_ACK. The coordinator collects all *acks* and begins phase II by sending the COMMIT message. This gets received by the non-coordinators in line 20, committing the change in line 22. A timer is set at the non-coordinators from phase I to phase II, to trap a possible failure of the coordinator. If this is the case, lines 15 through 19 describe the actions of the detector of the failure, while lines 24 through 28 describe the actions of the rest of the members in response.

```
1. process_msg (msg)
2.      select coordinator
3.      if coordinator
4.           /* phase I */
5.           rel_mlink (AGREE, AGREE_ACK, group)
6.           /* phase II */
7.           send COMMIT
8.           update internal state
9.      else                                                  /* non-coordinator */
10.          check if AGREE is for same change and drop if so
11.          send AGREE_ACK
12.          set timer for COMMIT
13.          do loop
14.               if timer expired                            /* current coordinator assumd to have failed */
15.                    send CO_FAIL to group                  /* process coordinator's failure */
16.                    send and receive status of members
17.                    elect new coordinator
18.                    process_msg (msg)
19.                    exit
20.               try to receive any message
21.               if msg = COMMIT
22.                    update internal state to reflect change
23.                    exit
24.               if msg = CO_FAIL
25.                    send and receive status of members
26.                    elect new coordinator
27.                    process_msg (msg)
28.                    exit
29.          end loop
```

Figure 21: Algorithm for Function "*process_msg*"

While this algorithm is simplified to hide the specific details of each different change processed, it gives an idea on the implementation of the protocols. Lines 18 and 27 show how recursion is used, so that any number of subsequent changes (like coordinators failing one after the other) get handled. The number of changes are limited only by the system's available memory, since any new recursive call reserves new space for all variables used. More detailed description is given at the code description section.

4. Code Description

a. Initialization

As in *mcaster*, it is vital to *mserver* to learn in its initialization phase if it runs on a host with multicast capability. The technique used in *mcaster* applied here also. After initializing the uc socket in line 2 of Figure 22, it tries to join an IGMP group on the class D address provided by the command line arguments as shown in lines 4 to 10. If this fails, no multicast is available and it is replaced by the *mcaster* in lines 12 to 16. As shown in Figure 16, one unicast socket is devoted to monitoring. The other socket is either multicast (multicasting is done in IP multicast extension layer) or unicast (multicasting is simulated by *mcaster*), according to the capability of the host *mserver* runs onto.

```
/* INITIALIZATION PHASE */
    uc = init_socket (&ucsin, PORT_UC);                /* Initialize unicast socket */
/* Join multicast IGMP group; if it cannot, then host is not MC capable */
    mc = init_socket (&mcsin, MC_PORT);                /* Initialize multicast socket */
    reply = join_mc_grp (mc, grpaddr);
    if (reply == JOIN_ACK) {
        setsockopt (mc, IPPROTO_IP, IP_MULTICAST_LOOP, &loop, sizeof (loop));
        lan = 1;
        mcaddr = grpaddr;
        mcport = MC_PORT;
    }
    else {
        lan = 0;
        mcaddr = mcaster;                              /* mcaster replaces mc lan */
        mc = init_socket (&mcsin, MS_PORT);
        mcport = MS_PORT;                              /* direct mc port to mcaster's */
    }
```

Figure 22: Code for Initializing Sockets of *Mserver*

b. New Member Join Procedure

After initializing the sockets and updating the internal list of *mcaster* (as described in Figure 17), *mserver* is about to send its first message to its *mserver* group. Figure 23 shows the code for joining the group. The communication with the group is done through a reliable link. New member is waiting for only one specific answer, a COMMIT message and uses *reliable_link* to send out its request and intercept the answer.

One common problem when a new member tries to join the *mserver* group is that the *mserver* group may be busy processing some other *mserver* group change of higher priority. If the network is slow (or a member is slow), then the current change may take some time to finish. Since this time is unpredictable, the solution of increasing the timeout time of the new member in line 3 does not cover all possible scenarios. A more intelligent code was implemented. The big loop between lines 9 and 34, suggests that the reliable link communication is tried two more times (making it a total of three, with the one of line 8). In between, any intercepted message is examined for its origin. If it comes from the *mserver* group, this means that the group is alive. Then the new member goes for another round, with a little longer waiting time, as suggested in line 32. This makes the new member more patient. On the other hand if no messages are heard from the *mserver* group, then as desceribed in lines 11 through 18, the new member creates its own group and initializes its internal state. It then exits the new member join procedure.

```
1. /*————NEW MEMBER JOIN PROCEDURE——————————*/
2.    max_retries = 3;            /* initialize retries and timeout */
3.    tout = T_M_JOIN_REQ;
4.    /* form M_JOIN_REQ message and socket address */
5.    form_messg (&msg, grpname, grpaddr, 0, 0, 0, M_JOIN_REQ, 0, NULL, 0, NULL, 0, NULL, 0);
6.    to.sin_family = AF_INET;
7.    to.sin_port = mcport;  to.sin_addr = mcaddr;  /* either mc or mcaster */
8.    mptr = reliable_link (&msg, to, uc, mc, COMMIT, max_retries, tout, mcaster, &f);
9.    for (i = 0 ; i < max_retries - 1; i++) {
10.       /* no msgs received at all, or no group msgs were listened */
11.       if (!mptr || (mptr && (mptr->grp_addr).s_addr != grpaddr.s_addr
12.                         && strcmp (mptr->group_name, grpname))) {
13.               myrank = 0;   myrow = 0;        /* assign rank 0 to itself */
14.               bzero ((char *)cs_tbl, tblen);/* put in core table itself */
15.               cs_tbl[0].addr = myaddr.s_addr;
16.               cs_tbl[0].rank = 0;     cs_tbl[0].cw = 0;
17.               cs_tbl[0].ccw = 0;      cs_tbl[0].flag = 1;
18.               break;
19.       }
20.       else {    /* some msg was received */
21.           if (!f) {                   /* it was the expected COMMIT */
22.               /* extract core table from commit msg */
23.               extract_init_state (mptr, &who, &n_req, cs_tbl);
24.               myrank = mptr->subject_gid;            /* find my rank and row of table I exist */
25.               for (i = 0; i < MAXTBLSIZE; i++)
26.                   if (cs_tbl[i].addr == myaddr.s_addr)
27.                       myrow = i;
28.               view = mptr->group_view;               /* adjust my view to change's view */
29.               break;
30.           }
31.           else {
32.               tout *= 6;    /* wait a little longer */
33.               mptr = reliable_link (&msg, to, uc, mc, COMMIT, max_retries, tout, mcaster, &f);
34.           }       } /* else */      } /* for */
```

Figure 23: Code for New Member Join Procedure

Of course, if at any time the long awaited message of type COMMIT comes in, the new member is accepted into the group. The COMMIT message carries the internal state of the coordinator updated to include the new member. Then the new member extracts this internal state and copies it to its own. Thus the new member is fully synchronized with the rest of the *mserver* group members.

c. *Monitoring - Processing Messages*

After an *mserver* becomes a member of an *mserver* group, the rest of its code is a loop, doing two major tasks: *Monitor* its clockwise member and *process* any incoming messages. Figure 24 shows this portion of the code. The loop starts in line 2 and ends in line 40. In line 4 *mserver* tries to read a message from the socket port. In lines 5 through 12 *mserver* processes any failed members recorded in the fail list. Monitoring is done in lines 13 through 28. There is an associated timer and when it expires, the member tries to monitor its clockwise member. Monitoring is not performed only when there is only one member in the group: There is no need for an *mserver* to look after itself. This is checked in line 14.

The incoming messages can be in one of three categories: 1) monitoring messages, 2) group change messages, and 3) application messages. Monitoring messages are part of the monitoring code. Group change messages are processed in the separate function *process_msg*. As shown in lines 35 and 37, application messages are also directed to the *process_msg* function which simply forwards them to the appropriate group.

There is also another important feature of the code in Figure 24: monitoring is executed only when no messages arrive at the ports of the *mserver*. This is achieved by inserting the monitor lines inside the *while* statement of line 4. If there are messages, this means that group members are active sending messages to each other and if there is any failure, it will be discovered through a reliable communication or a two-phase protocol. Therefore, additional monitoring is not needed.

d. *Function Process_Msg*

This function is the heart of the MS protocol. It includes a complete implementation of the two-phase protocol as well as the three-phase protocol to handle regular changes (joins - failures) and coordinator's failures. A separate function called by *process_msg* (to avoid long sequential code and to enhance the recursion) is function *process_co_fail* that handles the coordinator's failure. Both function declarations exist in "message.h" header file and their definitions in "message.c" file.

```
/*--------START MONITORING AND PROCESS OF INCOMING MSGS--------*/
for (;;) {                          /* big loop */
    /* try to receive any msg and process it; otherwise do monitor */
    while (recv_messg (uc, mc, &w, mcaster, &mptr, &from, t) <= 0) {
        while (fail_list) {                         /* see if there are failed members */
            form_messg (&msg, grpname, grpaddr, 0, view, myrank, AGREE_L,
                        fail_list->gid, NULL, 0, NULL, 0, NULL, 0);   /* form the AGREE_L msg */
        /* process the change (includes sending agree msg) */
            from.sin_addr.s_addr = 0;               /* deactivate from's address */
            process_msg (&msg, from);
            free (&msg);
        }
        if (timed_out (q_tout)) {                   /* see if it is time to tx a query */
            if (myrank != cs_tbl[myrow].cw) {       /* check if only one member in table */
                form_messg (&msg, grpname, grpaddr, 0, view, myrank, QUERY, 0, 0, 0, 0, 0, 0, 0);
                to.sin_family = AF_INET;            /* construct address of cw member */
                to.sin_port = htons (PORT_UC);
                to.sin_addr.s_addr = tblsrh (cs_tbl, cs_tbl[myrow].cw, 0)->addr;
                mptr = reliable_link (msg, to, uc, uc, REPLY, max_retries + myrank * 2,
                                      T_R_QUERY, mcaster, &f);
                free (&msg);  /* free space reserved for query msg */
                if (mptr ? (mptr->msg_type == QUERY) : 0)     /* see if somone is querying me */
                    break;
                if (f)                              /* no REPLY msg from cw member; fail it */
                    add_gid_entry ( &fail_list, cs_tbl[myrow].cw);
                free (mptr);                        /* free space allocated for reply msg */
            }
            set_timeout (&q_tout, T_QUERY);           /* set query (monitor) timer */
        }
    } /* while */
    switch (mptr->msg_type) {
    case QUERY:
        /* reply to query */
        break;
    default:
        /* process the msg */
        process_msg (mptr, from);
    } /* switch */
    free (mptr);
} /* big loop */
```

Figure 24: Code for the *Mserver*'s Main Loop

The algorithm for *process_msg* was presented in Figure 21. In that algorithm, all changes were treated in the same way, i.e., there was only one AGREE message for any kind of change. Each change has its own details that prohibit them from being encoded the same way. For example, the COMMIT message for a join carries the *mserver* group table as its data, because the new member depends on this message to extract the table and synchronize with the rest of the group. The COMMIT message for a fail does not have any data because the information for the failed member exists in the other fields of the message which is received by all surviving members.

In the current level of implementation, there are three kinds of change messages: a *join*, a *fail* (or leave) and a *coordinator fail*. Their *initiate* messages to start the change protocol are AGREE_J, AGREE_L and CO_FAIL correspondingly. There is only one AGREE_ACK to send as an acknowledgment for all of these types of initiate messages. Also, there is only one COMMIT for all changes although it may carry different data according to each case. To summarize the message descriptions (message fields not described are filled out normally):

- **AGREE_J** is the message issued by the lowest in rank active member upon reception of an M_JOIN_REQ group message as sent by a new member. This coordinator assigns a new rank to the new member, which copies to the *subject_gid* field of the message. The address of the new member gets copied to the *data* field and the *data_len* is adjusted. This message is sent out with the current *view* number.
- **AGREE_L** is the message issued by any member detecting (or suspecting) the failure of another member. In this case, the detector is the coordinator. So, if this message is originated from the *mserver*, this *mserver* is the coordinator. If the *mserver* received it, this *mserver* is a non-coordinator. No *data* is needed for this message. This message is sent out with the current *view* number.
- **CO_FAIL** is the message sent originally by any member detecting (or suspecting) the failure of the coordinator of the current change. In the status exchange phase that follows, each member sends a *co_fail* to exchange its status with the others. There is no *data* in this message but the *data_len* field is used to pass a 0 or 1 indicating that the status of the member sending the message is either "finished change (commited)" or still "processing the change" respectively.

- **AGREE_ACK** is the acknowledgment message sent at the end of phase I of the two-phase protocol. No special syntax is needed and it is common for every change. It is sent with the current *view*.
- **COMMIT** is the message sent always by the coordinator in the final phase of the change protocol. Although the same *msg_type* is used for all changes, there are some differences according to each case. If the change is a *Join*, then the current core-table of the coordinator (and of the group, since it is kept consistently in every member) gets copied to the *data* field of the message. Of course the *data_len* field is adjusted properly. If the change is a *Leave*, there is no need for any *data*. This message is always sent with a new *view* number (the current incremented by one).

Figure 25 shows the difference between the messages needed for a *join* and a *fail* change. In the first case, a two-phase protocol is initiated because an external message (*m_join_req*) gets received by the group. The decision for the coordinator is made in all *mservers* of the group. In the second case, the detector of a change (*fail*) initiates a two-phase protocol being itself a coordinator, which the other(s) accept.

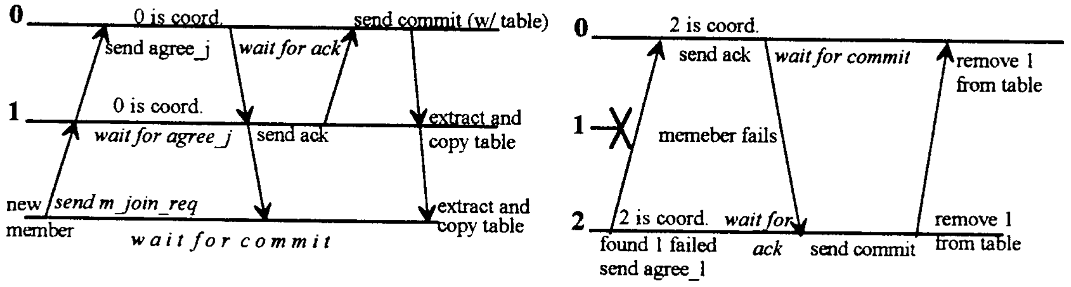


Figure 25: The Two-phase Protocol Time-lines for a *Join* and a *Fail*.

If the phase of receiving the *m_join_req* and deciding for the coordinator is omitted, then the logic between the two changes is similar. Next, the code for processing a *Join* is described pointing out the differences with the corresponding code for a *Fail*.

e. Processing Join Requests

Function *process_msg* has a "switch" as its first statement activating the appropriate portion of code according to the message type (*msg_type* field). As soon as an *m_join_req* is received by the group, all members execute the part of code shown in

Figure 26. The election of the coordinator is based on the rank. The lowest rank active member gets elected. The function to elect the coordinator, *elect_coord*, is also shown in Figure 26. All *mservers* not elected as coordinator exit the case statement and return to normal idling state. The elected coordinator continues and starts the two-phase protocol by forming and broadcasting the AGREE_J message to the group. The non-coordinators receive the message and process it. Figure 27(a) shows the code for the coordinator, while Figure 27(b) shows the code for the non-coordinators.

```
case M_JOIN_REQ:
    if (tblsrh (cs_tbl, 0, from.sin_addr.s_addr))      /* check if it is a duplicate */
        break;
    if (myrank != elect_coord (cs_tbl))             /* see if I am coordinator; if not discard msg */
        break;
------------------------------------------------------------
u_short  elect_coord (tbl)
    struct table_entry  *tbl;
{
    int         i;
    u_short  lr = 65535;
    for (i = 0; i < MAXTBLSIZE; i++)
        if (tbl[i].addr)
            if (lr > tbl[i].rank && tbl[i].flag)    /* lowest rank active member in table is elected */
                lr = tbl[i].rank;
    return lr;
}
```

Figure 26: Receiving a New *Mserver* Request for Join and Electing Coordinator

It must be clear that a lot of error-checking code has been omitted here to clarify the specific points of discussion. Also part of the code is slightly modified so that it is presented in a more complete form.

The two-phase protocol code would work in all cases if we had a totally fail-proof environment. Unfortunately, one or more *mservers* of the group may fail while processing a change. If a non-coordinator member fails during phase I, then the coordinator finds it out in line 7 of Figure 27(a). Since it is discovered by the end of phase I of the current change, it is ensured that the failure of the member is of lower priority [28, 29]. The failed member is added to the failed list and processed later.

```
1./* COORDINATOR */
2./* find a new gid for new member */
3.nr = cs_tbl[myrow].ccw + 1;
4.data = form_change_info (from.sin_addr.s_addr);
5.form_messg (&msg, mptr->group_name, mptr->grp_addr,
    0, view, myrank, AGREE_J, nr, NULL, 0, NULL, 0, data,
    sizeof (u_long));
6./* send it to mserver group; phase I */
7.fail_list = rel_mlink (&msg, group, uc, mc, AGREE_ACK,
    tries, cs_tbl, fail_list, 3*SEC, mcaster);
8./* if acks received proceed to phase II */
9.free (data);              free (&msg);
10.add_table_entry (cs_tbl, from.sin_addr.s_addr);
11.data = form_init_state (from.sin_addr.s_addr, 0, cs_tbl,
    NULL, 0);
12.len = MAXTBLSIZE * sizeof (struct table_entry) + sizeof
    (int) + sizeof (u_long);
13.form_messg (&msg, mptr->group_name,
    mptr->grp_addr, 0, ++view, myrank, COMMIT, nr, NULL,
    0, NULL, 0, data, len);
14.send_messg (mc, &msg, group);
15.free (data);
16.free (&msg);
```

(a)

```
1./* NON-COORDINATOR */
2.case AGREE_J:
3./* extract info about new member */
4.extract_change_info (mptr, &mbr);
5./* ack the join */
6.form_messg (&msg, mptr->group_name, mptr->grp_addr,
    0, view, myrank, AGREE_ACK, mptr->subject_gid, NULL, 0,
    NULL, 0, NULL, 0);
7.from.sin_port = htons (PORT_UC);
8.send_messg (uc, &msg, from);
9./* wait for commit */
10.if ( recv_messg (uc, mc, &w, mcaster, &rmsg, &who, tr) >
    0) {
11.        if (rmsg->msg_type == COMMIT &&
12.        rmsg->group_view == view + 1 &&
13.        rmsg->subject_gid == mptr->subject_gid) {
14.            /* adjust view to last change */
15.                view = rmsg->group_view;
16.                /* extract new core table */
17.                extract_init_state (rmsg, &mbr,
18.                                    &nrq, cs_tbl);
19.                break; /* exit case */
20.        } /* if commit */
21.} /* if */
```

(b)

Figure 27: Code for AGREE_J for the Coordinator and the Non-Coordinator.

f. Processing Coordinator's Failure

The coordinator can also fail during a change. First, the other members must learn about the failure. This is done by timing out the waiting cycle for a *commit* message. If the coordinator fails, then at least one non-coordinator member times out while waiting for the *commit* and assumes that the coordinator failed. Then it forms and sends out a *co_fail* message, which includes its status. Then it enters the *process_co_fail* function which is decscribed in Figure 28. The other members may be in the same position waiting for a *commit* or may have committed already (depending on how far into the change protocol the original coordinator has gone). Upon receipt of the *co_fail* message, they also enter the *process_co_fail* function.

In the function itself there are three sections. In the first section (lines 4 through 35), the exchange of *co_fail* messages and collection of status for all members of the group takes place. In the second (lines 37 through 46), a new coordinator is elected and the members that did not reply are added to the fail list. The lowest rank member that completed phase I of the original change (sending an *ack*) becomes the new coordinator. The third section looks like an ordinary two-phase protocol, like the one for the *join* shown in Figure 27. It is omitted from Figure 28 for compactness.

In the exchange of the status section, each member sends its status with the broadcast of a *co_fail* message as in line 23 and then tries to receive the same message from every other member in the group. The *co_fail* message uses the *data_len* field of the mesage to carry an integer showing the status of the member with respect to the current change. All answers are placed into an array and they are processed later in the election phase.

The lowest rank active member that has finished phase I of the current change but not committed, is elected as the new coordinator. Then if at least one member has committed the current change, it is marked at line 40. Depending on this, the new coordinator will decide if it will go through a complete three-phase protocol if none of the group members had commited, or will use the compressed three-phase protocol if at least one of them had. After finishing with the original change the failure of the old coordinator is being processed as usual with the same new coordinator starting a two-phase change protocol.

The change described here in Figures 27 and 28 is a new member's *Join.* Almost the same code can be used for a *Leave,* occuring when a member fails. The slight differences are already described in subsection (d) of this section.

D. REMARKS

The current level of *mserver* implementation takes care of the *Join, Leave* and *Coordinator's (of a Join) failure* changes. Implementation of a coordinator's failure while processing a failure is expected to be similar. Additional changes may be added when the implmentation will expand to include top-down hierarchy messages (parent-child relations). The code described here can be used as a guide to implement the processing of any new messages. The compilation, running and testing of this code is described in the Appendix.

```
void process_co_fail (mptr, p_mptr)
    struct message          *mptr, *p_mptr;
{ . . .
/* reset reply table and count active members in group */
    n_mbrs = 0;
    for (i = 0; i < MAXTBLSIZE; i++) {
        r[i] = -1;
        if (cs_tbl[i].flag && cs_tbl[i].addr)
            n_mbrs++;
    }
/* subtract detector and mark its answer */
    n_mbrs -= 1;
    r[mptr->sender_gid] = mptr->data_len;
/* if other than detector, subtract me also */
    if (myrank != mptr->sender_gid) {
        n_mbrs -= 1;
        r[myrank] = p_mptr ? 1 : 0 ;
    }
    mptr->sender_gid = myrank;/* adjust sender's gid into msg to reflect me */
/* send co_fail msg and collect answers; re-send maxtries times */
    for (i = 0; i < MAXTRIES; i++) {
        n_mbrs -= n_ans;  n_ans = 0;
        send_messg (mc, *mptr, group);
        if (!n_mbrs)        break;          /* if all answers received, stop */
        while (n_ans < n_mbrs && !timed_out (t))  /* receive until all reply or time expires */
            if (recv_messg (uc, mc, &w, mcaster, &rmsg, &who, tr) > 0) {
                /* see if must listen to received msg and if received msg is coord_fail */
                if (tblsrh (cs_tbl, 0, who.sin_addr.s_addr) &&
                    rmsg->group_view == view &&
                    rmsg->msg_type == COORD_FAIL) {
                    n_ans++;
                    /* update reply table */
                    r[rmsg->sender_gid] = rmsg->data_len;
            }    }    /* if - if */
        set_timeout (&t, T_COFAIL);
    } /* for */
/* elect new coordinator based on answers */
    for (i = 0; i < MAXTBLSIZE && cs_tbl[i].addr; i++) {
    /* mark if a member has commited */
        if (!r[i])    commit = 1;
    /* new coord must have replied and been in agree phase */
        if (r[i] == 1)              /* member in agree phase */
            if (elected > cs_tbl[i].rank)    elected = cs_tbl[i].rank; /* elect lowest rank */
            if (r[i] == -1)  /* put in fail list members that did not reply */
                add_gid_entry (&fail_list, cs_tbl[i].rank);
    }
. . .
} /* process_co_fail */
```

Figure 28: Code for Function *Process_Co_Fail*.

V. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

This thesis presented an implementation of two basic components of the MS, the *mcaster* and the *mserver*. A set of useful MS-related utility functions was implemented and each one tested independently. These functions were organized in different files, providing good modularity and portability of the code.

A complete working *mcaster* was implemented and tested to work in uc-mc mixed as well as uc-only LANs, handling one or more groups. The present version of *mcaster* is capable of propagating correctly any kind of group messages.

The *mserver* implemented is capable of creating and maintaining an *mserver* group at one level. New member joins and failures are handled correctly and according to the protocol.

B. FUTURE WORK

There are a lot of possible paths for follow-up work. First, to demonstrate that the MS is truly scalable to global proportions, a parent-child model must be added to the *mserver*, and tested on progressively larger scales. To achieve this, the basic *mserver* model presented in this thesis must be enhanced to include handling of messages related to the parent-child model. Also the internal state of the *mserver* must be enriched to support these relations. The functions developed for the current implementation can be used as a basis for future development.

Second, the partition resolution protocol must be implemented and tested since it is one of the strong advantages of the MS. A strategy to test partition handling without failing the network will need to be designed.

Third, a complete performance analysis of the operation, overhead, network constraints, service latency and functionality of the MS must be accomplished. Also, an implementation of an MI is needed to provide the *mserver* group the necessary interface to applications groups.

Fourth, an Application Programmer's Interface (API) as described in [28], must be defined completely and implemented, to give a tool to programmers to use the MS. Using this API, the next step is to create some test applications to take advantage of the MS use.

Finally, the MS architecture must be revisited in the future, to take advantage of the reliable, high-speed networks, which are currently being deployed. Advances in network technology, such as ATM (Asynchronous Transfer Mode) and Sonet (Synchronous optical network), provide a different network model than the conventional IP-based model used for the design of this MS.

APPENDIX. COMPILE, RUN AND TEST THE MS

A. COMPILING

Table I provides the names of the files currently used in the MS implementation, and a short description of the contents and the names of the functions defined in each file.

Filename	Associated header	Description	Included Files	Functions
msutil.c	msutil.h	Definitions of global constants Definitions of structures Utilities collection	None	*leave_mc_grp, join_mc_grp, init_socket, addrcmp, form_messg, send_messg, recv_messg, receive_msg, set_timeout, timed_out, search_gid_list, add_gid_entry, copy_gid_list, extract_gid_list, delete_gid_list, print_in_addr, print_sock_addr, print_sock_info, print_hostent, print_messg, print_gid_list, print_nps_logo, make_chksum, chk_chksum*
mcaster.c	–	Multicast emulator program	msutil.h	*search_group_list, search_member_list, add_group, add_member, join_group, remove_group, remove_member, leave_group, mcast, print_group_list,print_member_list*
msutil2.c	msutil2.h	Utilities collection used by mserver program only	msutil.h	*tblsrh, add_table_entry, rm_table_entry, rm_fail_entry, exctract_init_state, form_init_state, extract_change_info, form_change_info, print_core_table, elect_coord*
reliable.c	reliable.h	Definitions and declarations of reliable link functions	msutil.h	*reliable_link, rel_mlink*
message.c	message.h	Definitions and declarations of message processing functions	msutil.h msutil2.h reliable.h	*process_msg, process_co_fail*
mserver.c	–	Mserver main program	msutil.h msutil2.h reliable.h message.h	*None*

Table I: Description of the Files for the MS

To compile the above files, the ANSI C compiler (*acc*) was used over in CC department. There are a lot of different hosts in the CC network and not all of them have the IP multicast extensions [30] installed. If these extensions are not installed then it is not possible to compile the *msutil.c* file (specifically the *join_mc_grp* function) and subsequently, all the files that include it.

Table II gives some of the hosts on the NPS Computer Center LAN, their type and their Internet address. If the compilation takes place on a specific type of machine (SUN or SGI), then the programs can run only on the same type of machine.

Name	Type	Internet Address	IP Multicast
alioth.cc.nps.navy.mil	SGI	131.120.53.2	Yes
merak.cc.nps.navy.mil	SGI	131.120.53.5	Yes
megrez.cc.nps.navy.mil	SUN	131.120.53.8	Yes
acamar.cc.nps.navy.mil	SUN	131.120.53.80	Yes
sp25420x[1] .cc.nps.navy.mil	SUN	131.120.254.20x	Yes
in502yy[2] .cc.nps.navy.mil	SUN	131.120.50.2yy	No

[1] x = 1, 2, ... , 8

[2] yy=11, 12, ... , 17

Table II: Host Machines on NPS Computer Center LAN

All files must be in the same directory at the compilation time. If a file is in a different directory, the path must be included in the *#include* directive. To compile and link successfully a file that includes other files, all those files must previously be compiled without problems. For example, if a change has been made to *mserver.c* file, the command line for the compilation should read:

```
%> acc -c mserver.o mserver.c
%> acc -o mserver mserver.o msutil.o msutil2.o reliable.o message.o
```

If a change has occurred in the *msutil.c* file then the sequence of commands should be:

```
acc -c msutil.o msutil.c
acc -c msutil2.o msutil2.c
acc -c reliable.o reliable.c
acc -c message.o message.c
acc -c mserver.o mserver.c
acc -o mserver mserver.o msutil.o msutil2.o reliable.o message.o
```

For this purpose, it is better to use a Makefile. A sample Makefile is in the *~mservice/cc* directory. To debug the files using the debugger, the *-g* option switch must be included in all lines of compiling, so that the compiler generates information for debugging.

B. RUNNING

After successful compilation, it is time to run the *mservers*. As many command tool windows as the *mservers* that are going to run plus one more for the *mcaster* are needed. The remaining procedure is as follows:

1. Remote login (*rlogin*) to a different host from each command tool window.
2. Run *mcaster* at one of these hosts and mark its IP address printed at the end of the initialization of *mcaster*. The *mcaster* must run on a mc host, if there are going to be servers running on mc hosts. If there are no hosts running on uc hosts, then *mcaster* is not needed.
3. Start the first *mserver* as described on page 33. The creation of a new group takes a couple of seconds, since the *mserver* tries to find out if other members exist.
4. Start the rest of the *mservers*, delaying the second one 15 seconds after the first one. The *mservers* should join sequentially and each one should print its own core-set table, which should be the same at every place. At the same time, the *mcaster* shows the traffic of the messages going through its channels.
5. *Mservers* should monitor each other in a ring schema as described by the monitor protocol. Monitoring query takes place every one minute for each *mserver*.

C. TESTING

At this level of implementation, the following tests can be performed and their results can be observed:

1. **Add a new member:** Open a new command window, remote login to a host not in use by other *mservers* or *mcaster* and start a new *mserver* program. The join request shall appear in every member of the group. The lowest rank member is the coordinator. It proceeds with the two-phase protocol and finally the new *mserver* is accepted as seen in the core-table printed in every member, that contains the information for the new member.
2. **Leave (fail) a member:** With a group running, go to a command window and kill one of the *mservers*. Soon the *mserver* monitoring the failed one will discover the failure and start a two-phase protocol, with itself being the

coordinator. In the end, every member prints its own core-table in which the information for the failed member has been removed.

3. **Make a member slow:** In a command window running an *mserver*, suspend (CTRL-Z) the process. Wait until monitoring finds out. After the process of the fail, recover the suspended member. After a while, it tries to monitor its clockwise member (of the old group), which denies to accept the query and does not respond. Then sequentially, the suspended and recovered member fails all the members of the old group. In the end, it is alone in its own group, while the other members run their own group. The problem of naming the two different groups has not been solved yet.

4. **Add a new member and fail another while in the process of join:** Before starting the join, kill a member and immediately (before monitoring finds out about the fail) start a new *mserver* to join. The coordinator finds out about the fail from the two-phase protocol for the join and adds the failed member to the failed list. After completing the new member's join, the coordinator process the fail as usual.

5. **More than one groups running at the same time:** Start and setup two different groups of one or more *mservers* each. The two groups should differ in the class D address or the group name or both. After the setup, both groups function independently. All above scenarios can run in one or both groups at the same time.

6. **Failure of the coordinator of a join:** To run this test case, a special version of an *mserver* program is needed. Make a faulty *mserver* (called *fmserver*) that has some code lines that simply delay just before the second phase of the join protocol. Since the protocols are described in file *message.c*, such delay lines should be added there as shown in Figure 29. Set up a group as usual, running the *fmserver* as the first (lowest rank) member. Then start a new *mserver*. While the *fmserver* receives all responses from members and delays (end of phase I) kill it. The other members timeout for the commit message. The first that times out, starts a three phase protocol by broadcasting a *co_fail* message. After that, all members exchange status through subsequent *co_fail* messages. Then the join of the new member gets processed. 'In the end the old coordinator (fmserver) gets failed and removed from the group and core-table.

```
/* file MESSAGE.C */
. . .
case M_JOIN_REQ:
. . .
            /* if acks received proceed to phase II; form COMMIT */
            free (data);
            free (&msg);
/* -- FAULTY SERVER GETS SLOW -- */
sleep (3);
. . .
/* send COMMIT */
. . .
```

Figure 29: Delaying a Faulty *Mserver (Fmserver)* to Test Coordinator's Failure

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