US008335813B2

(12) **United States Patent**
Sun et al.

(10) **Patent No.: US 8,335,813 B2**
(45) **Date of Patent: Dec. 18, 2012**

(54) **SYSTEMS, METHODS, AND PROTOCOLS FOR PROCESS MIGRATION AND GROUP MEMBERSHIP MANAGEMENT**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 634 days.

(21) Appl. No.: **12/045,546**

(22) Filed: **Mar. 10, 2008**

(65) **Prior Publication Data**

US 2008/0273457 A1 Nov. 6, 2008

Related U.S. Application Data

(60) Provisional application No. 60/915,324, filed on May 1, 2007.

(51) **Int. Cl.**
G06F 15/16 (2006.01)

(52) **U.S. Cl.** **709/201**

(58) **Field of Classification Search** 709/201, 709/202, 203
See application file for complete search history.

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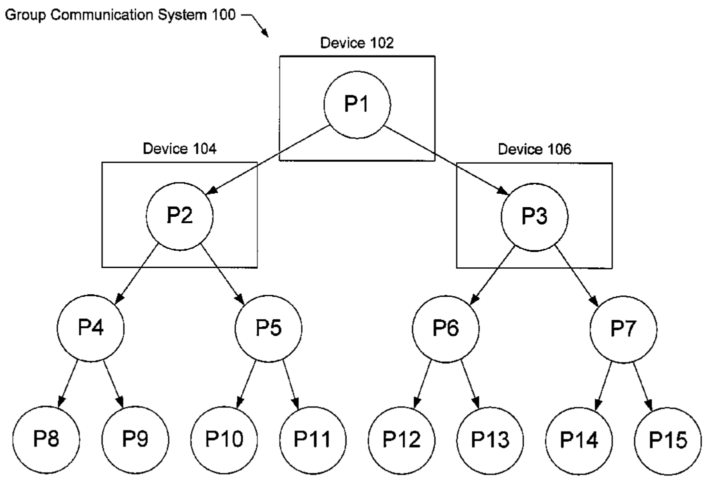
(57) **ABSTRACT**

A system, method, and set of protocols for dynamic group communication are provided for enabling dynamic process migration and dynamic group membership management. A process in a group receives and distributes a migration signal. Group communication continues while the processes in the group asynchronously reach a global superstep and then a synchronization point. The processes then spawn a new process on a new device and update group membership information. The new process operates in continuous execution with the new group.

22 Claims, 12 Drawing Sheets



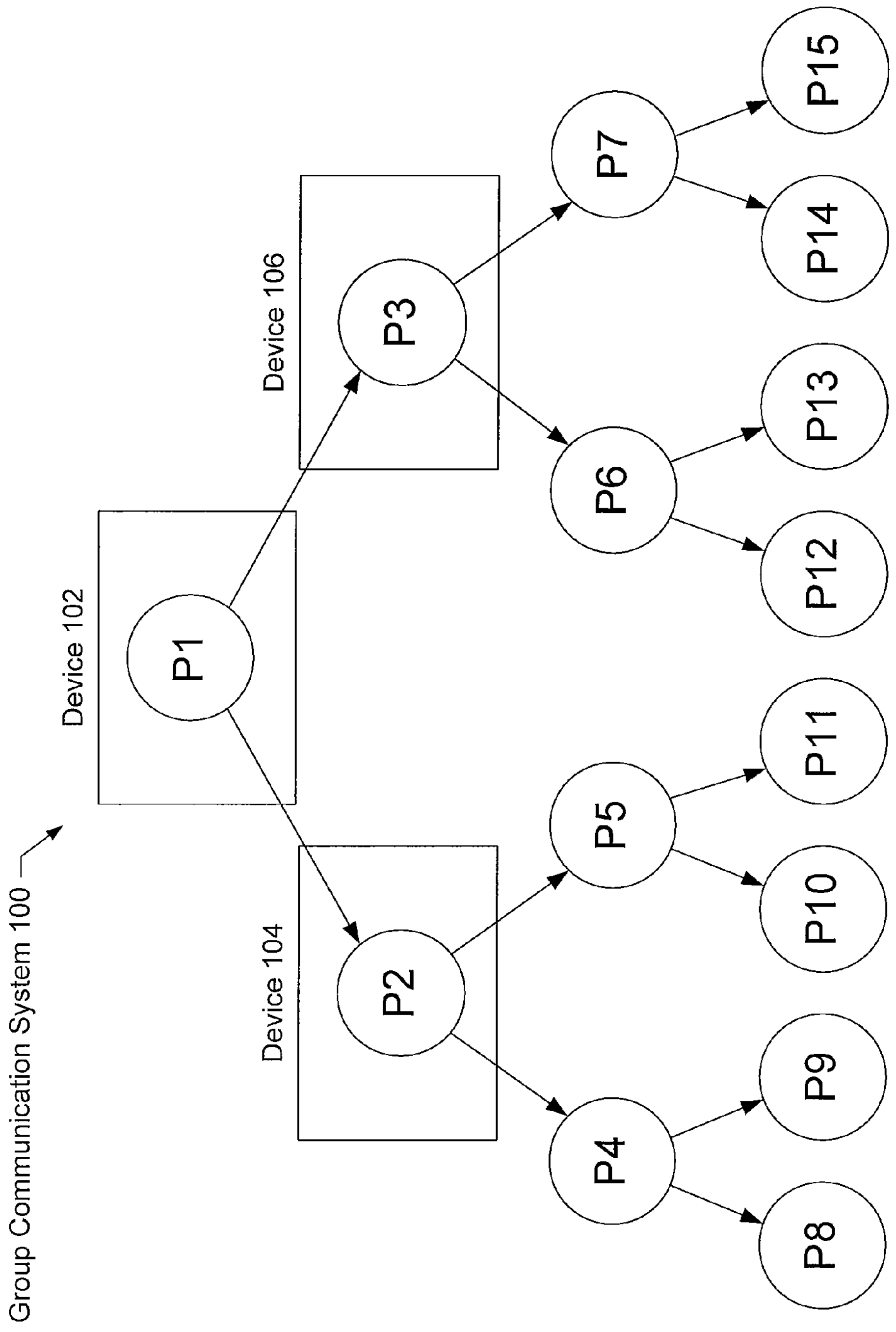
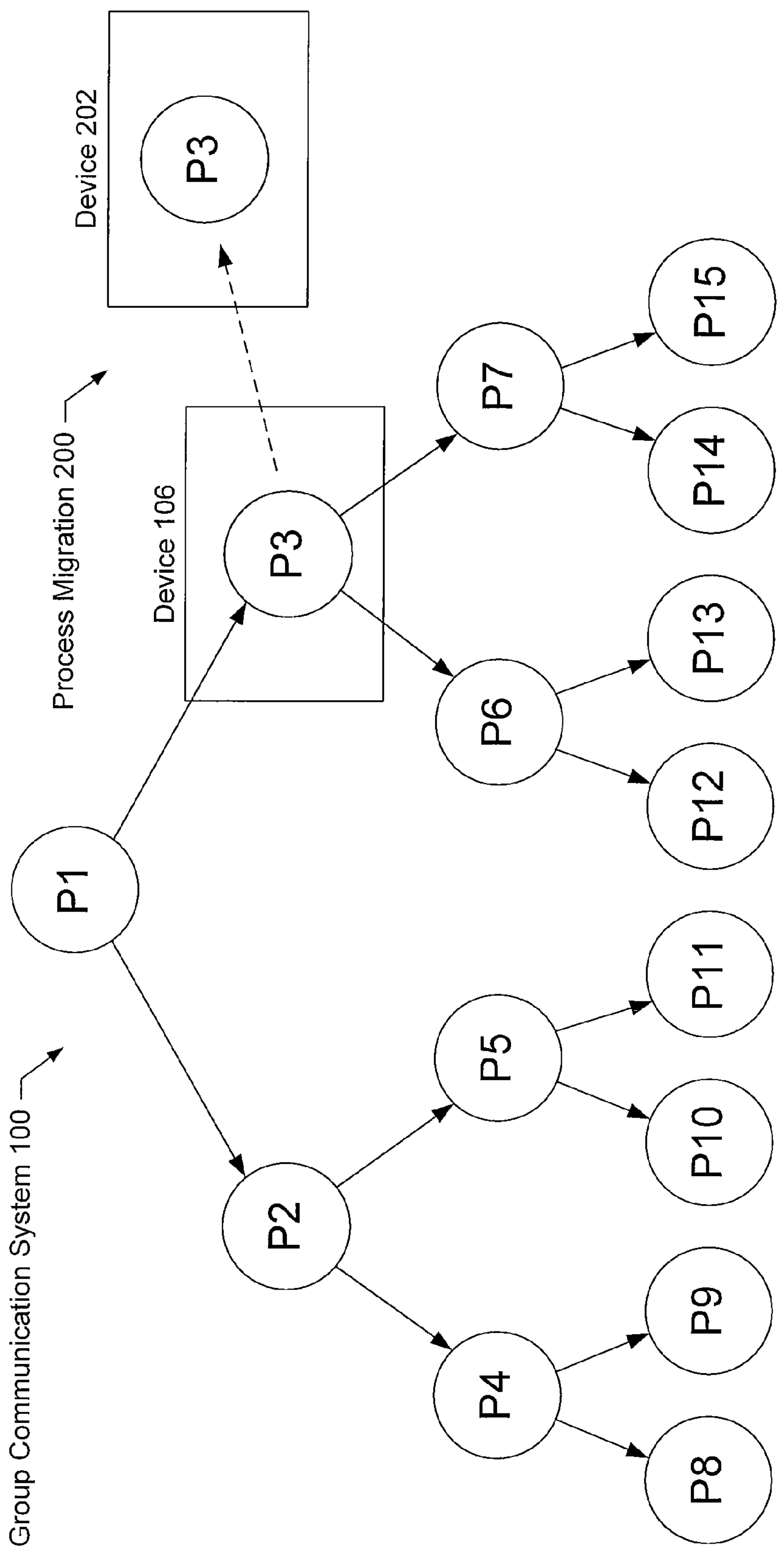

Group Communication System 100
Device 102
Device 104
Device 106
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10
P11
P12
P13
P14
P15

Figure 1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Process Migration 200
Device 106
Device 202
P1
P2
P3
P3
P4
P5
P6
P7
P8
P9
P10
P11
P12
P13
P14
P15

Figure 2

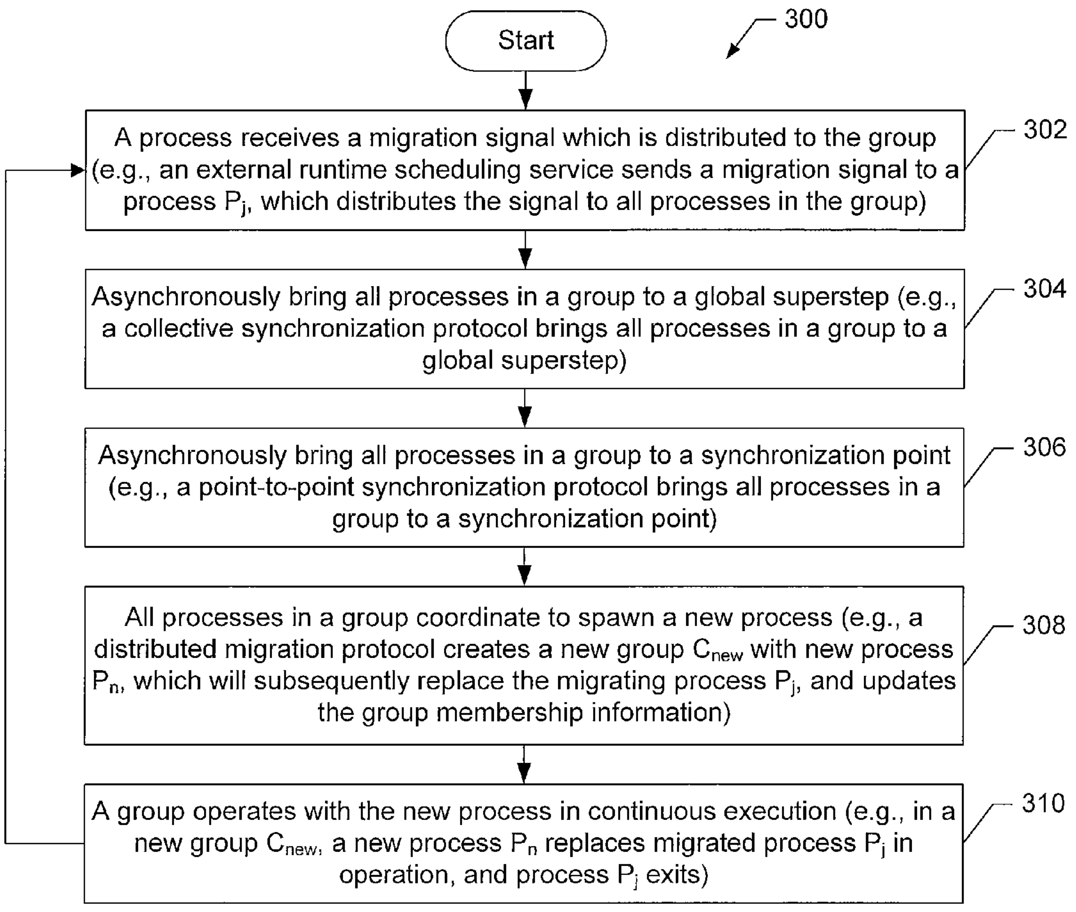
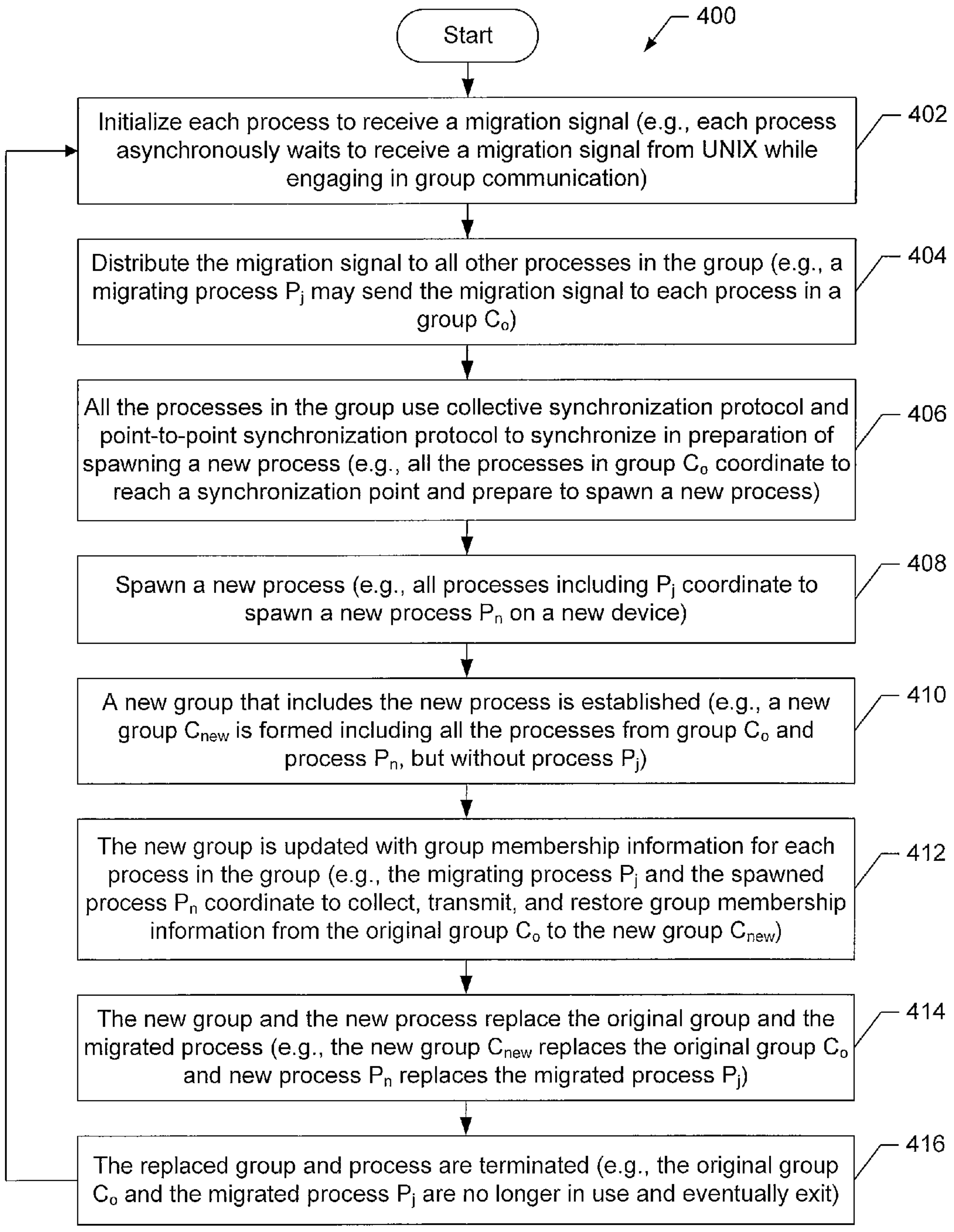

300
Start
A process receives a migration signal which is distributed to the group (e.g., an external runtime scheduling service sends a migration signal to a process P_j, which distributes the signal to all processes in the group)
302
Asynchronously bring all processes in a group to a global superstep (e.g., a collective synchronization protocol brings all processes in a group to a global superstep)
304
Asynchronously bring all processes in a group to a synchronization point (e.g., a point-to-point synchronization protocol brings all processes in a group to a synchronization point)
306
All processes in a group coordinate to spawn a new process (e.g., a distributed migration protocol creates a new group C_{new} with new process P_n, which will subsequently replace the migrating process P_j, and updates the group membership information)
308
A group operates with the new process in continuous execution (e.g., in a new group C_{new}, a new process P_n replaces migrated process P_j in operation, and process P_j exits)
310

Figure 3



400
Start
402
Initialize each process to receive a migration signal (e.g., each process asynchronously waits to receive a migration signal from UNIX while engaging in group communication)
404
Distribute the migration signal to all other processes in the group (e.g., a migrating process P_j may send the migration signal to each process in a group C_o)
406
All the processes in the group use collective synchronization protocol and point-to-point synchronization protocol to synchronize in preparation of spawning a new process (e.g., all the processes in group C_o coordinate to reach a synchronization point and prepare to spawn a new process)
408
Spawn a new process (e.g., all processes including P_j coordinate to spawn a new process P_n on a new device)
410
A new group that includes the new process is established (e.g., a new group C_{new} is formed including all the processes from group C_o and process P_n, but without process P_j)
412
The new group is updated with group membership information for each process in the group (e.g., the migrating process P_j and the spawned process P_n coordinate to collect, transmit, and restore group membership information from the original group C_o to the new group C_{new})
414
The new group and the new process replace the original group and the migrated process (e.g., the new group C_{new} replaces the original group C_o and new process P_n replaces the migrated process P_j)
416
The replaced group and process are terminated (e.g., the original group C_o and the migrated process P_j are no longer in use and eventually exit)

Figure 4

Figure 5

500
DISTRIBUTED MIGRATION
PROTOCOL

```
C = {<$P_0$, $P_1$,...$P_{n-1}$ >}: Initiation
Initiation()
Begin
Asynchronously waiting for migration notification;
End

$P_j$: On migration signal to migrate to machine $m$
OnMigration()
Begin
  Send a migration notification ($MIG\_CMD\ P_j$) to each process $P_i$ in application $App$
  = {$P_0$, $P_1$,...$P_{n-1}$ }
  CollectiveSyn();
End

$P_i$ : where $P_i \in \{P_0, P_1, \ldots P_n\}$; C= {<$P_0$, $P_1$,...$P_{n-1}$ >}: Reaching a synchronization
point
$P_n$ : After Initiated;  $P_j$ : In migration
CommUpdate()
Begin:
  If ( $i < n$ ) then
    Collectively spawn a new process $P_n$;
  Else if ( $i == n$ ) then
    Process initiation
   End if
  Collectively establish a new group $C_{new}$ = {<$P_0$, $P_1$, $P_{j-1}$, $P_n$, $P_{j+1}$...$P_{n-1}$ >};
  Replace $C$ with $C_{new}$;
  If ( $i == j$ ) then
    Local process state collection;
    Send communication state to $P_n$;
    Send local process state to $P_n$;
    Process finalization
  Else if ( $i == n$ ) then
   Receive communication state from $P_j$;
    Receive local process state from $P_j$;
    Process state restoration;
    Reset migration and synchronization flags;
  Else
    If $P_i$ is awakened
      Repeat pending pt2pt operation $op$;
     Endif
    Reset migration and synchronization flags;
  End if
End
```

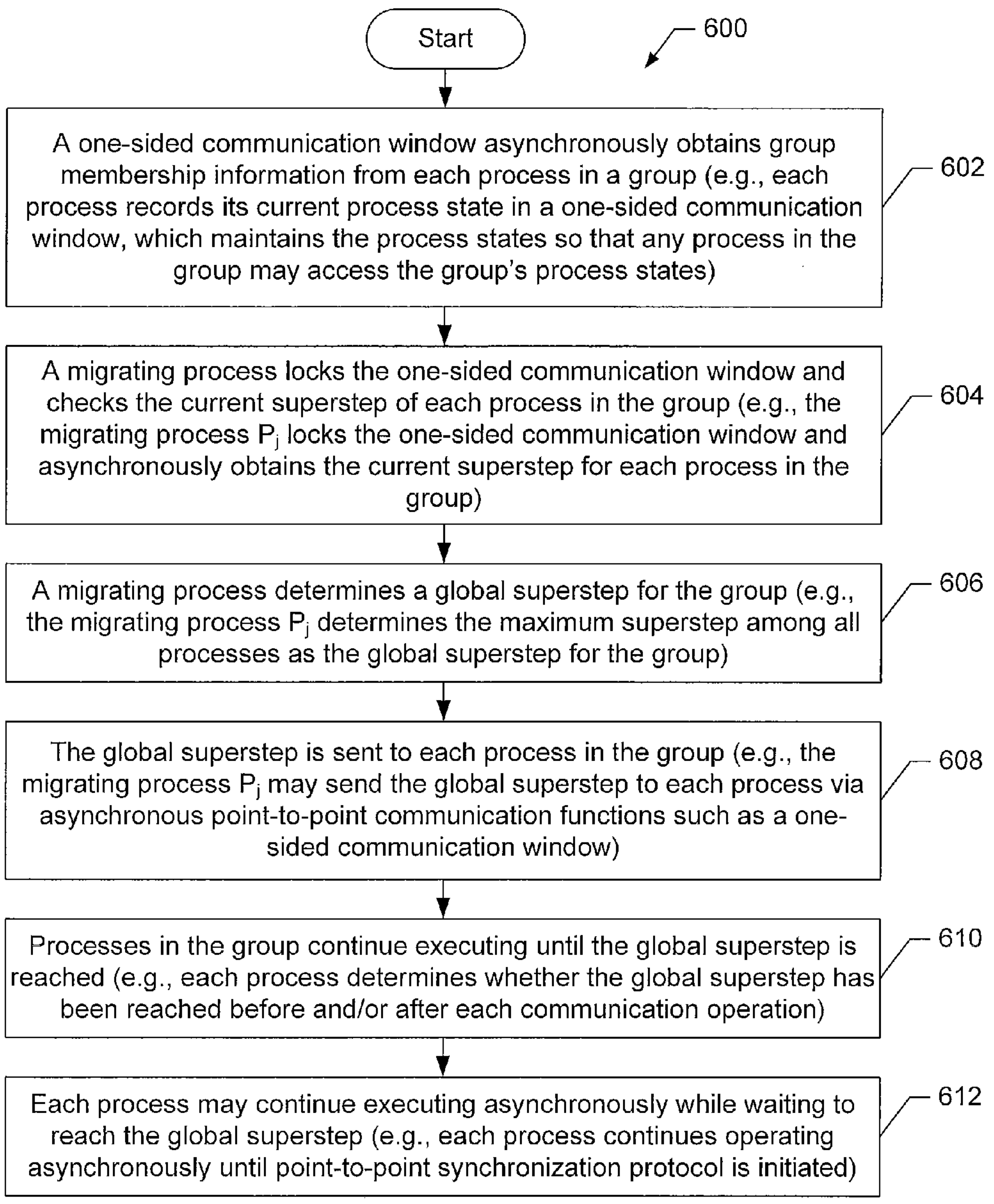

600
Start
A one-sided communication window asynchronously obtains group membership information from each process in a group (e.g., each process records its current process state in a one-sided communication window, which maintains the process states so that any process in the group may access the group's process states)
602
A migrating process locks the one-sided communication window and checks the current superstep of each process in the group (e.g., the migrating process P_j locks the one-sided communication window and asynchronously obtains the current superstep for each process in the group)
604
A migrating process determines a global superstep for the group (e.g., the migrating process P_j determines the maximum superstep among all processes as the global superstep for the group)
606
The global superstep is sent to each process in the group (e.g., the migrating process P_j may send the global superstep to each process via asynchronous point-to-point communication functions such as a one-sided communication window)
608
Processes in the group continue executing until the global superstep is reached (e.g., each process determines whether the global superstep has been reached before and/or after each communication operation)
610
Each process may continue executing asynchronously while waiting to reach the global superstep (e.g., each process continues operating asynchronously until point-to-point synchronization protocol is initiated)
612

Figure 6

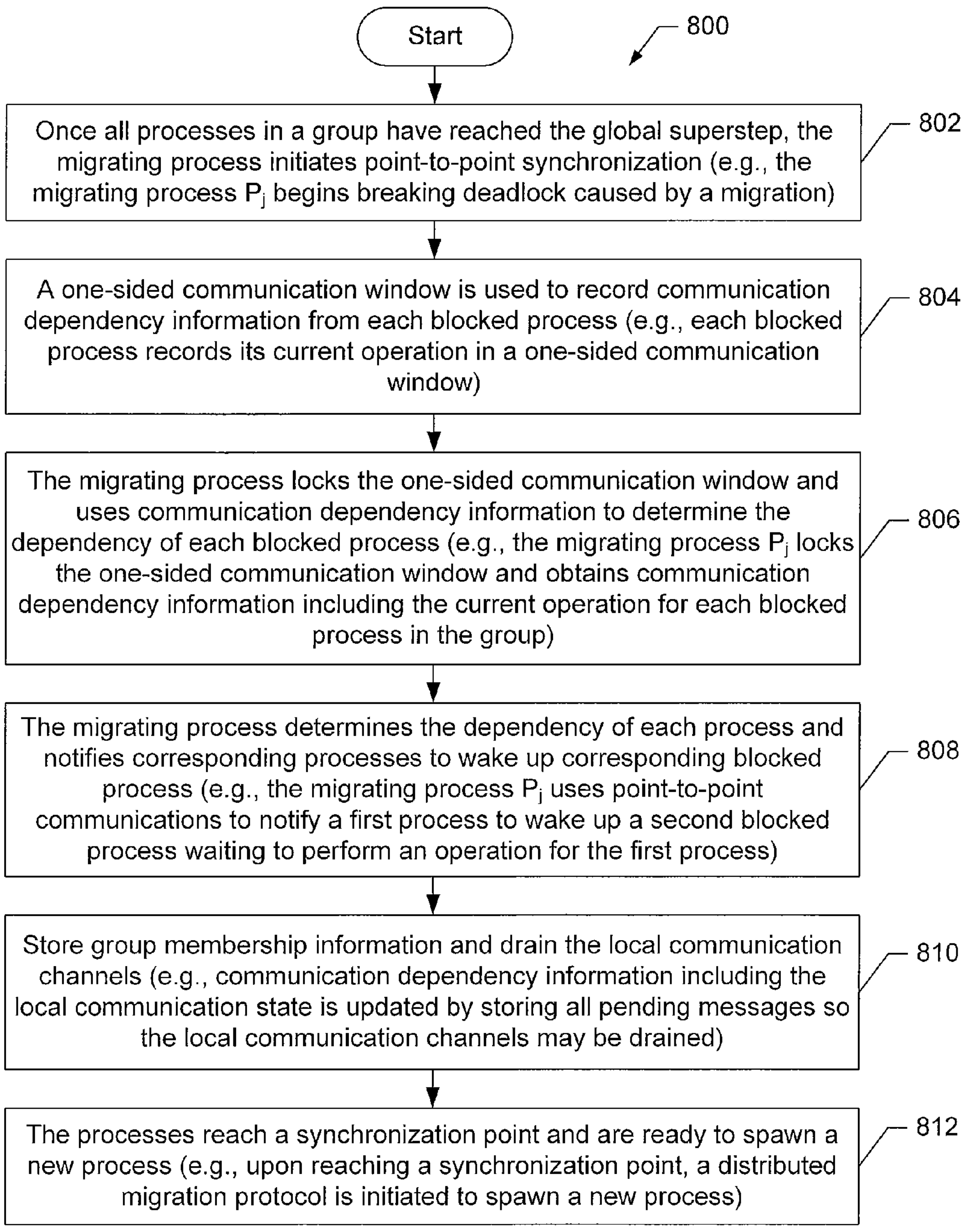
700
COLLECTIVE
SYNCHRONIZATION
PROTOCOL

Figure 7

```
Pj: After distributing the migration cmd;
CollectiveSyn()
Begin
  Lock super_step for read;
  step = 0;
  For i = 0 to n-1 do
    If ( super_step_i > step) then
      step = super_step_i;
    End if
  End for
  For i = 0 to n-1 do
    If ( i <> j ) then
      Send step to Pj
    End if
  End for
  Unlock super_step
End
```

```
Pi: Before entering a collective communication; where Pi ∈ {P0, P1,... Pj-1, Pj+1 ...Pn-1};
BeforeCollective()
Begin
  Test migration cmd;
  If ( cmd == MIG_CMD Pj ) then
    Recv migration cmd;
    Recv global_superstep from Pj;
  End if
  If ( superstep == global_superstep ) then
    P2Psyn();
  End if
  Increase superstep;
End
```

```
Pi: After a communication operation; where Pi ∈ { P0, P1, ...Pn-1 };
AfterOp()
Begin
  If (Pi is in synchronization phase and
  superstep == global_superstep) then
    P2Psyn();
  End if
End
```



Start
800
Once all processes in a group have reached the global superstep, the migrating process initiates point-to-point synchronization (e.g., the migrating process P_j begins breaking deadlock caused by a migration)
802
A one-sided communication window is used to record communication dependency information from each blocked process (e.g., each blocked process records its current operation in a one-sided communication window)
804
The migrating process locks the one-sided communication window and uses communication dependency information to determine the dependency of each blocked process (e.g., the migrating process P_j locks the one-sided communication window and obtains communication dependency information including the current operation for each blocked process in the group)
806
The migrating process determines the dependency of each process and notifies corresponding processes to wake up corresponding blocked process (e.g., the migrating process P_j uses point-to-point communications to notify a first process to wake up a second blocked process waiting to perform an operation for the first process)
808
Store group membership information and drain the local communication channels (e.g., communication dependency information including the local communication state is updated by storing all pending messages so the local communication channels may be drained)
810
The processes reach a synchronization point and are ready to spawn a new process (e.g., upon reaching a synchronization point, a distributed migration protocol is initiated to spawn a new process)
812

Figure 8

900
POINT-TO-POINT
SYNCHRONIZATION
PROTOCOL

Figure 9

```
$P_i$: reaching the global super step where $P_i \in \{P_0, P_1, \ldots P_{n-1}\}$;
P2PSyn()
Begin
  If ( i == j) then
    Lock current_op for read;
    For k = 0 to n-1 do
      If $P_k$ is block waiting for $P_x$, then
        If (x == j ) then
          wake $P_k$;
        Else
          send MIG_WAKE $P_k$ to $P_x$;
        End if
      End if
      For k = 0 to n-1 do
        If ( k <> j ) then
          send MIG_END  to $P_k$;
        End if
      End for
    End for
    Unlock current_op;
  Else
    Receive cmd from $P_j$;
    While ( cmd == MIG_WAKE $P_k$ ) Do
      wake $P_k$;
    End while
    Assert (cmd == MIG_END);
  Endif
  If $P_i$ is awakened,
    Mark the previous pt2pt operation op as pending;
  Endif
  Drain local communication channel and save the data as local communication state;
  CommUpdate()
End
```

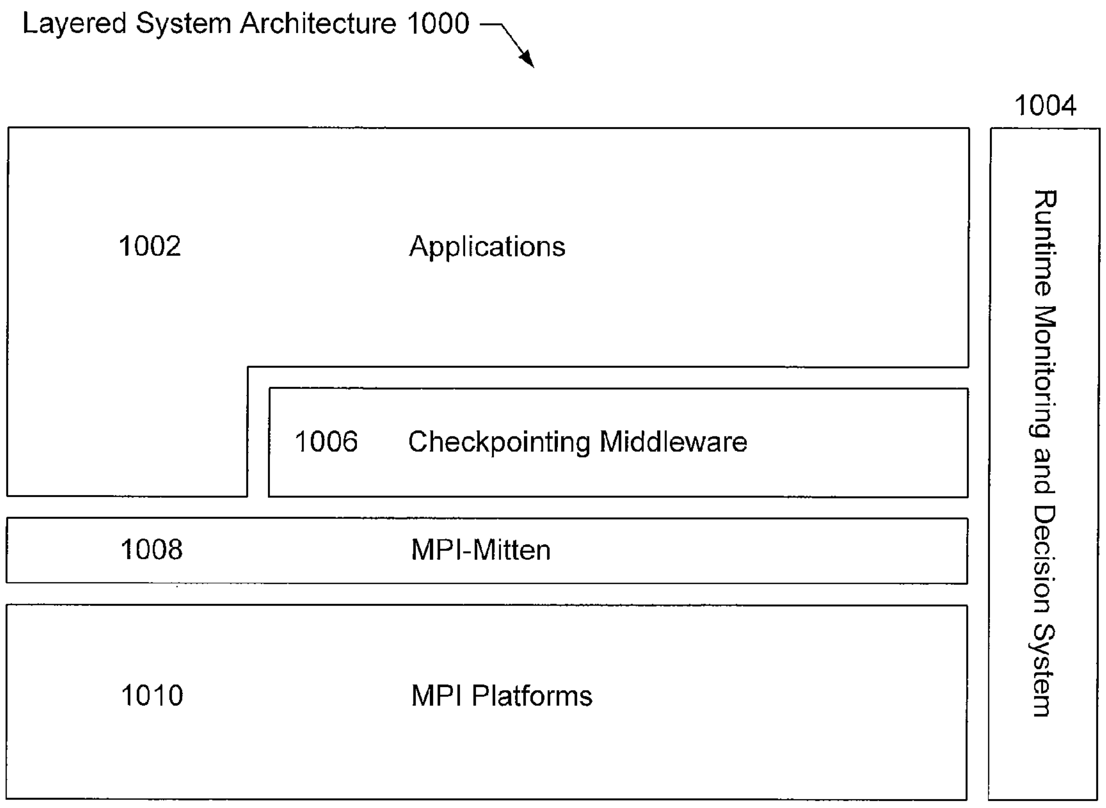

Layered System Architecture 1000
1004
1002
Applications
1006
Checkpointing Middleware
1008
MPI-Mitten
1010
MPI Platforms
Runtime Monitoring and Decision System

Figure 10

Figure 11

1100
MPI-MITTEN
OVERHEAD

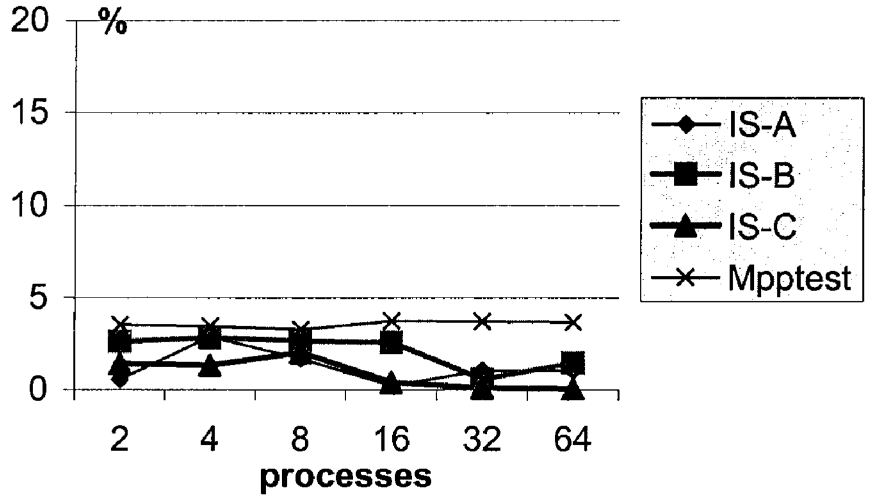


Figure 12

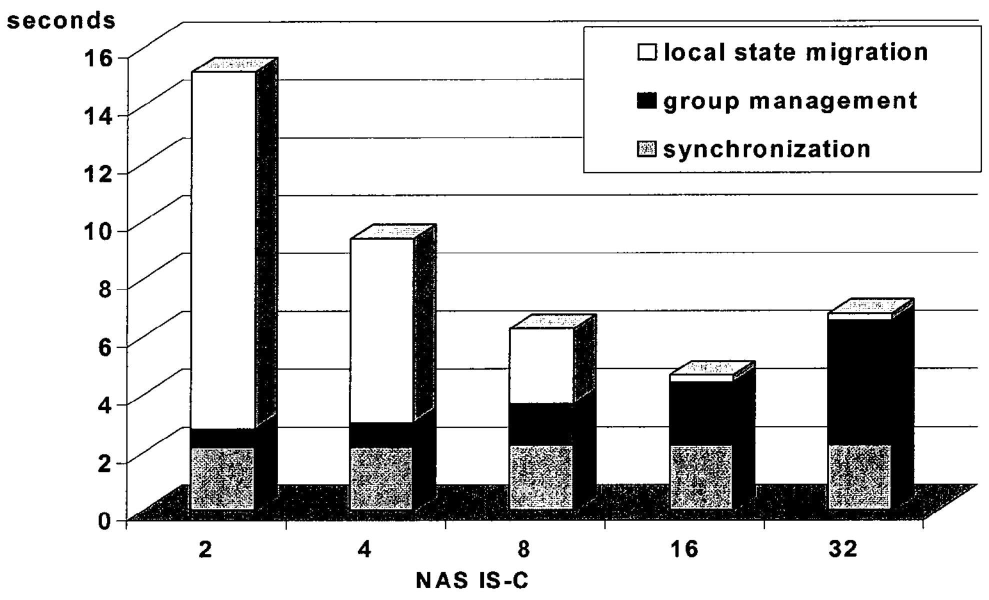
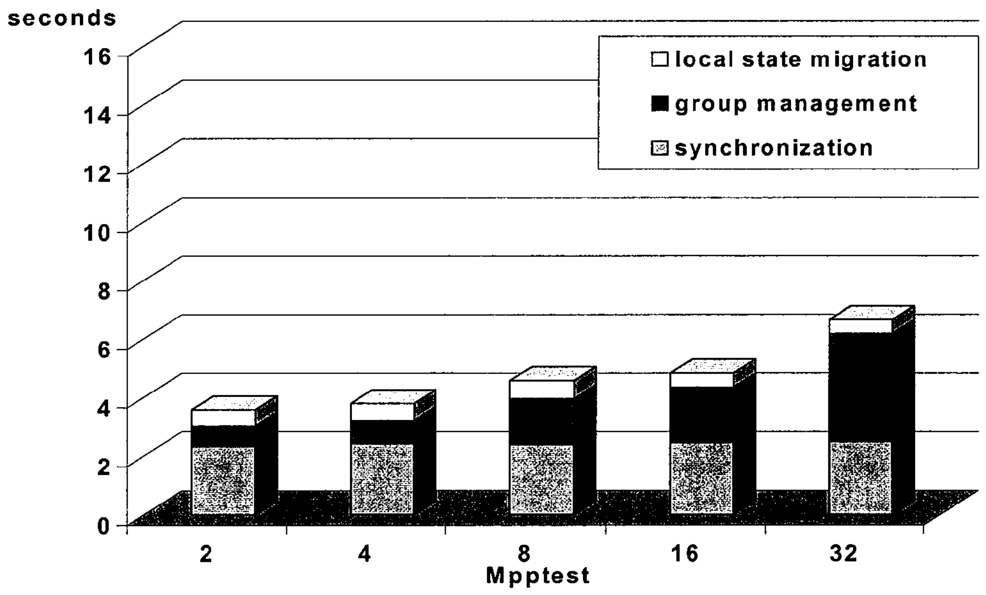


Figure 13



SYSTEMS, METHODS, AND PROTOCOLS FOR PROCESS MIGRATION AND GROUP MEMBERSHIP MANAGEMENT

RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 60/915,324, filed May 1, 2007 entitled "Systems, Methods, and Protocols for Process Migration and Group Membership Management", the contents of which are hereby incorporated by reference.

TECHNICAL FIELD

The present application relates in general to process migration and group membership management and more specifically to dynamic group communication with dynamic process migration and dynamic group membership management.

BACKGROUND

Recent advances in computing technologies have allowed an increasing number of computing devices to communicate, work collectively, and manage processes via a network in order to provide services that may otherwise not be available. However, in this coordinated environment, the service provided by a group of processes located on different devices and working together can fail due to a single point of failure. The failure rate increases as the number of computing devices hosting processes increases, making it increasingly more important to provide a means for fault tolerance and continued group communication.

Fault tolerance can be supported by migrating a process from a failing device to a stable device, in order to provide continued service. In addition to migrating the process, the group membership information must be updated to account for the migrated process. Typically, migrating a process requires finishing all pending communications and stopping all group communication while the migration occurs. The amount of time a migration takes depends on various factors. The interruption in group communication may cause problems for a user such as service interruptions. The cost of an interruption caused by migration may be high, particularly in a distributed mobile environment.

Modern computing devices are likely to be mobile devices, which communicate and receive service through local service stations. When a mobile device moves, its local service station may change. Changing the service station requires process migration and updating the group membership information. Current mobile computing is limited when the computing involves communication among multiple processes on multiple computers, where the processes are involved in group communication, due to the interruption in group communication associated with a process migration.

Mobility is an integral part of modern information services. For instance, when a user participates in a conversation using a mobile phone on a train, the user will probably pass several mobile service stations, which will provide the mobile phone with a communication signal. Typically, the transfer of the communication signal from each service station to the next should be transparent to the user. Computing works similarly in that a piece of software can be downloaded automatically when needed, or can move from one computing device or service station to another in order to provide continued service. Another example of group communication requiring the mobility of a computing device is when multiple users participate in an online game concurrently and interactively

through multiple computers. If one of the users moves from one service station to another service station, all communications with that particular user may be lost. The user will not be able to continue to participate in the game without a service interruption unless all processes from the first service station are transparently migrated to the second service station and the group membership information is updated.

SUMMARY

The systems, methods, and protocols disclosed herein provide an improvement to providing increased fault tolerance and transparent service to a user with dynamic group communication. Migrating a process without halting group communication requires dynamic group communication. Dynamic group communication is a form of group communication that allows for dynamically synchronizing all processes in a group, dynamically migrating a process located on a failing device, and dynamically updating the group membership information, in order to provide uninterrupted group communication and transparent service.

Group communications are commonly used in networked computing where multiple users and/or processes need to coordinate and work collectively, however, existing migration mechanisms do not support dynamic group communications. Typically, group communication mechanisms stop all communication prior to the migration of the process and then restart communication after the migration is completed. Stopping communication may not allow for transparent process migration, so conventional approaches struggle to keep up with the pace of many commercial applications, such as computer gaming. Dynamic group communication can instead be used to support continued service by moving processes, software, etc. from a failing device to a working device without halting group communications. Dynamic group communication allows processes to operate asynchronously while preparing for the process migration so group communications continue during the migration. In this fashion, there is not a large backup of communications following a migration, and the migration is transparent to the user.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a block diagram of an example group communication system.

FIG. **2** is a block diagram of an example group communication system with a process migration.

FIG. **3** is a flowchart of an example dynamic group communication protocol.

FIG. **4** is a flowchart of an example distributed migration protocol.

FIG. **5** is an outline of a source code implementation of an example distributed migration protocol.

FIG. **6** is a flowchart of an example collective synchronization protocol.

FIG. **7** is an outline of a source code implementation of an example collective synchronization protocol.

FIG. **8** is a flowchart of an example point-to-point synchronization protocol.

FIG. **9** is an outline of a source code implementation of an example point-to-point synchronization protocol.

FIG. **10** is a block diagram of an example layered system architecture.

FIG. **11** is an example graphical illustration of MPI-Mitten overhead for the NAS IS benchmark and for the Mpptest benchmark.

FIG. **12** is an example graphical illustration of the efficiency and scalability of dynamic process migration of an embodiment of the present disclosure for the NAS IS benchmark.

FIG. **13** is an example graphical illustration of the efficiency and scalability of dynamic migration of an embodiment of the present disclosure for the Mpptest benchmark.

DETAILED DESCRIPTION

The present disclosure introduces example systems, methods, and protocols to handle dynamic group communication of processes. Protocols are preferably implemented as a thin-layered modular software component designed to run on top of non-migration-supported communication protocols.

FIG. **1** is a block diagram of an example group communication system **100**. The processes P**1** through P**15** may be located on various remote devices. For example, P**1** may be located on device **102**, P**2** may be located on device **104**, P**3** may be located on device **106**, etc. One or more processes may reside on one or more devices, and two or more processes may form a group such that the processes may communicate through a message passing interface and perform various operations. For example, process P**1** communicates messages via group communication to each other process in the group (P**2** through P**15**). In this example, P**1** sends a message to P**2** and P**3**, then P**2** and P**3** each send the message to two more processes, and so on until each process receiving a message receives the message. It should be appreciated that many methods and protocols may be used for group communication and many group membership management goals may be achieved through various methods and protocols. For example, the processes that receive a message and the order of sending messages may be altered depending on the various system factors such as efficiency, fault tolerance, system capabilities, communication infrastructure, etc.

FIG. **2** is a block diagram of an example group communication system **100** with a process migration **200**. Process P**1** communicates messages via group communication to each other process in the group (processes P**2** through P**15**) and process P**3** migrates from device **106** to device **202**. In order for group communication to continue without interruption, when process P**3** migrates to the new device **202**, the group membership information is updated so process P**3** may continue to receive and send messages. Group membership information is information relating to the processes that are members of the group. In an embodiment, the group membership information includes information about the processes that form a group, such as the communication state, local process states, process identifiers, device IP addresses, communication dependency information, etc. Group membership management is the management of the group, including managing which processes are group members, synchronization procedures, what each process does with the group, the updating of the group membership information, etc. Group membership management allows group communication to continue. When group membership information is updated, the group membership management may provide different communication algorithms, process ranks, etc. in light of the updated group membership information and the group membership management goals. It should be appreciated that if process P**3** cannot send or receive messages, group communication may be interrupted and cause communication failures resulting in delays and/or failures of one or more processes. Typically, while process P**3** migrates, the rest of the processes stop communicating, so for example, processes P**1** and P**2** may not communicate during a process migration **200**. Once process P**3** has migrated, the group membership information is updated, then the group continues communications. Dynamic group communication allows the processes in the group to continue communicating while process P**3** migrates and while the group information is updated. For example, with dynamic group communication, while process P**3** migrates, processes P**1** and P**2** may communicate, processes P**2** and P**4** may communicate, processes P**4** and P**8** may communicate, etc. Using dynamic group communication, a large backup of communications typically caused by a process migration **200** may be avoided because all communications do not stop during the process migration **200**. Dynamic group communication thus allows for more efficient and transparent process migration **200**.

FIG. **3** is a flowchart of an example dynamic group communication protocol **300**. Although the protocol **300** is described with reference to the flowchart illustrated in FIG. **3**, it will be appreciated that many other methods of performing the acts associated with protocol **300** may be used. For example, the order of many of the blocks may be changed, and many of the blocks described are optional.

The example dynamic group communication protocol **300** is comprised of three sub-protocols, a distributed migration protocol, a collective synchronization protocol, and a point-to-point synchronization protocol. In the example dynamic group communication protocol **300**, a distributed migration protocol causes a process to receive a migration signal, which is distributed to the group (block **302**). For example, each process in a group is waiting to receive a migration signal and an external runtime scheduling system sends a migration signal to a process P_j. Preferably, the process P_j then sends the migration signal to each other process in the group and each process agrees to the migration. Example embodiments of the distributed migration protocol are depicted in FIGS. **4** and **5** and described below. Next a collective synchronization protocol asynchronously brings all processes in a group to a global superstep (block **304**). Example embodiments of the collective synchronization protocol are depicted in FIGS. **6** and **7** and described below. Once all the processes in the group are at the global superstep, a point-to-point synchronization protocol asynchronously brings all processes in the group to a synchronization point (block **306**). Example embodiments of a point-to-point synchronization protocol is depicted in FIGS. **8** and **9** and described below. A distributed migration protocol causes all the processes to coordinate to spawn a new process (block **308**). For example, a distributed migration protocol creates a new group C_{new} with new process P_n, which will subsequently replace the migrating process P_j, and updates the group membership information. Once the group membership information is updated, the group operates with the new process in continuous execution (block **310**). For example, in the new group C_{new}, the new process P_n replaces the migrated process P_j in operation, and process P_j exits. The group may perform another dynamic process migration **200** upon receiving another migration signal.

FIG. **4** is a flowchart of an example distributed migration protocol **400**. Although the protocol **400** is described with reference to the flowchart illustrated in FIG. **4**, it will be appreciated that many other methods of performing the acts associated with protocol **400** may be used. For example, the order of many of the blocks may be changed, and many of the blocks described are optional. In this example, the original group C_o contains a number of processes on various devices, the processes including process P_j. The group C_o can communicate within the group and with other groups using point-to-point operations and collective operations.

In the example distributed migration protocol **400**, each process is initialized to asynchronously receive a migration signal (block **402**). For example, while participating in group communication, each process asynchronously waits to receive a migration signal from UNIX indicating that the process should migrate to a new device. Each process may asynchronously receive the migration signal in a variety of ways, such as from a UNIX signal, a monitoring daemon, a shared file system, or another process in the group. Once a migrating process receives a migration signal, it distributes the migration signal to all other processes in the group (block **404**). For example, a migrating process P_j may send the migration signal to each process in the group C_o. It should be appreciated that processes do not need to be synchronized to send or receive a migration signal. Preferably, processes only synchronize when a process is preparing to migrate. All the processes in the group use collective synchronization protocol and point-to-point synchronization protocol to synchronize in preparation of spawning a new process (block **406**). For example, all the processes in group C_o coordinate to reach a synchronization point and prepare to spawn a new process. A collective synchronization protocol and a point-to-point synchronization protocol will be described in more detail below. Once the group is synchronized, a new process is spawned (block **408**). For example, all processes including P_j coordinate to spawn a new process P_n on a new device. Once a new process is spawned, a new group that includes the new process is established (block **410**). For example, a new group C_{new} is formed including all the processes from group C_o and process P_n, but without process P_j. A new group may be formed using the MPI_Comm_Spawn function. The new group is updated with group membership information for each process in the group (block **412**). For example, the migrating process P_j and the spawned process P_n coordinate to collect, transmit, and restore group membership information from the original group C_o to the new group C_{new}. Typically, a new group is updated with the group membership information for each process in the group. The group membership information is used for group membership management, such as regulating the processes' status, communications, operations, etc., both within the group and outside of the group. The new group and the new process replace the original group and the migrated process (block **414**). For example, the new group C_{new} replaces the original group C_o and new process P_n replaces the migrated process P_j. It should be appreciated that the new group may consist of the same exact processes with the exception of the migrated process, which has changed devices, however, in operation, the new group C_{new} and new process P_n collectively replace the original group C_o and migrated process P_j. The replaced group and process are terminated (block **416**). For example, the original group C_o and the migrated process P_j are no longer in use and eventually exit.

FIG. **5** is an outline of a source code implementation of an example distributed migration protocol **500**. Although the protocol **500** is described with reference to the outline illustrated in FIG. **5**, it will be appreciated that many other methods of performing the acts associated with protocol **500** may be used. For example, the order of the source code may be changed, and portions of the source code described are optional.

The example distributed migration protocol **500** may be used for updating group membership information and group membership management. In the example distributed migration protocol **500**, each process in group C is initialized to asynchronously receive a migration signal. Once process P_j receives a migration signal, process P_j sends a migration notification (MIG_CMD P_j) to each other process in group C. Once a synchronization point is reached, the processes reach a consensus to spawn a new process. Then, the processes collectively spawn a new process P_n. The new process P_n is initialized. Then the processes collectively establish a new group C_{new}. The new group C_{new} includes the newly spawned process P_n. It should be appreciated that establishing a process or new group may consist of one or more operations. For example, establishing a new group may be accomplished by first establishing an intercommunicator from the group C, and then establishing an intracommunicator as the new group C_{new}. Further, it should be noted that a process may be in more than one group and/or communicator at once. Once the new group C_{new} is established, C_{new} will replace the old group C. The migrated process P_j collects group membership information, coordinates with the new process P_n, and sends the group membership information to process P_n to restore and/or update the group membership information at group C_{new}. The new process P_n replaces P_j in operation and P_j will exit at some point. Any point-to-point operations pending for an awakened process P_i in the group C_{new} may be repeated. It should be appreciated that following a migration, each process may use the updated group membership information, for example to determine the communication state before receiving a message from their communication channel and to finalize communication channels. All processes in group C_{new} may reset migration flags and synchronization flags. Group C_{new} continues operating with process P_j in its new location.

FIGS. **6**, **7**, **8**, and **9** are representations of example embodiments of synchronization protocols. The example synchronization protocols allow the processes in the group, which may be running independently and asynchronously, to reach a synchronization point in order to migrate a process involved in group communication. In an embodiment, synchronization is performed in two phases using a collective synchronization protocol and a point-to-point synchronization protocol. Synchronization protocol causes all processes in a group coordinate to reach the same superstep. Point-to-point synchronization causes all processes coordinating to reach a synchronization point within the superstep. In an embodiment, a superstep may be defined by the execution block between any two collective operations. An execution block is a sequence of operations performed by a process. Within a superstep, processes may send messages only through point-to-point communication channels.

FIG. **6** is a flowchart of an example collective synchronization protocol **600**. Although the protocol **600** is described with reference to the flowchart illustrated in FIG. **6**, it will be appreciated that many other methods of performing the acts associated with protocol **600** may be used. For example, the order of many of the blocks may be changed, and many of the blocks described are optional.

In the example collective synchronization protocol **600**, a one-sided communication window asynchronously obtains group membership information from each process in a group (block **602**). For example, each process records its current process state in a one-sided communication window, which maintains the process states so that any process in the group may access the group's process states. Once a migration signal has been distributed to all of the processes, a migrating process locks the one-sided communication window and checks the current superstep of each process in the group (block **604**). For example, the migrating process P_j locks the one-sided communication window and asynchronously obtains the current superstep for each process in the group. Then, a migrating process determines a global superstep for the group (block **606**). For example, the migrating process P_j

determines the maximum superstep among all processes as the global superstep for the group. The global superstep is sent to each process in the group (block **608**). For example, the migrating process P_j may send the global superstep to each process via asynchronous point-to-point communication functions such as a one-sided communication window. Processes in the group continue executing until the global superstep is reached (block **610**). For example, each process determines whether the global superstep has been reached before and/or after each communication operation. Each process may continue executing asynchronously while waiting to reach the global superstep (block **612**). For example, each process continues operating asynchronously until point-to-point synchronization protocol is initiated.

FIG. **7** is an outline of a source code implementation of an example collective synchronization protocol **700**. Although the protocol **700** is described with reference to the outline illustrated in FIG. **7**, it will be appreciated that many other methods of performing the acts associated with protocol **700** may be used. For example, the order of the source code may be changed, and portions of the source code described are optional. It should be appreciated that the protocol **700** is merely one example outline of source code that may embody the example collective synchronization protocol **600** described above.

FIG. **8** is a flowchart of an example point-to-point synchronization protocol **800**. Although the protocol **800** is described with reference to the flowchart illustrated in FIG. **8**, it will be appreciated that many other methods of performing the acts associated with protocol **800** may be used. For example, the order of many of the blocks may be changed, and many of the blocks described are optional.

In the example point-to-point synchronization protocol **800**, once all processes in a group have reached the global superstep, the migrating process initiates point-to-point synchronization (block **802**). For example, the migrating process P_j begins breaking deadlock caused by a migration. It should be appreciated that communications may be blocked for a process that has pending communications which were not performed because the process was waiting for the global superstep and/or waiting to receive a communication from another process that is directly or indirectly blocked by the migration. The migrating process P_j may determine the dependency of each process on the other processes in the group. A one-sided communication window is used to record group membership information from each blocked process (block **804**). For example, each blocked process records its current operation in a one-sided communication window. The migrating process locks the one-sided communication window and uses group membership information to determine the dependency of each blocked process (block **806**). For example, the migrating process P_j locks the one-sided communication window and obtains communication dependency information including the current operation for each blocked process in the group. The migrating process determines the dependency of each process and notifies corresponding processes to wake up corresponding blocked process (block **808**). For example, the migrating process P_j uses point-to-point communications to notify a first process to wake up a second blocked process waiting to perform an operation for the first process. For example, the migrating process P_j may wake up a blocked process P_k with a command such as MIG_WAKE P_k. Once all processes are awake, store group membership information and drain the local communication channels (block **810**). For example, communication dependency information including the local communication state is updated by storing all pending messages so the local communication channels may be drained. The communication channels are typically defined as the pathways for communication utilized by the underlying platform and are bidirectional, First-In, First-Out (FIFO). A command such as MIG_END may signal that all processes are awake, and cause the group membership information to be stored and communication channels drained. Once the pending messages are stored, the processes have reached a synchronization point and are ready to spawn a new process (block **812**). For example, upon reaching a synchronization point, a distributed migration protocol **400** is initiated to spawn a new process.

FIG. **9** is an outline of a source code implementation of an example point-to-point synchronization protocol **900**. Although the protocol **900** is described with reference to the outline illustrated in FIG. **9**, it will be appreciated that many other methods of performing the acts associated with protocol **900** may be used. For example, the order of the source code may be changed, and portions of the source code described are optional. It should be appreciated that the protocol **900** is merely one example outline of source code that may embody the example point-to-point synchronization protocol **800** described above.

It should be appreciated that many of the processes performed by the example protocols may be overlapping and/or performed by a different protocol than the example protocols describe. For example, a distributed migration protocol **400** and/or a point-to-point synchronization protocol **800** may overlap when pending operations are repeated in a new group after waking up a blocked process.

FIG. **10** is a block diagram of an example layered system architecture **1000**. System **1000** is typically compatible with existing parallel programming environments. System **1000** preferably employs Message Passing Interface (MPI) primitives to create communication protocols that may synchronize processes, manage and update groups, and maintain a consistent global communication state during a process migration. MPI Primitives are basic operations supported by MPI standards. Example layered system architecture **1000** includes MPI-Mitten **1008**, a thin, high-level, add-on layer positioned between application layer **1002** and MPI Platform layer **1010**.

MPI-Mitten **1008** may be implemented as a portable communication library that enhances an application with dynamic group membership management that manages processes to increase fault tolerance. MPI standards define many collective primitives and may allow primitives to be optimized for various hardware platforms to achieve better performance. Dynamic group membership management functions, such as process spawning, merging, and splitting, and one-sided communication functions, such as put and get, are supported by underlying MPI platforms. Examples of underlying platforms include Local Area Multicomputer MPI (LAM/MPI) and MPI Chameleon 2 (MPICH2), although any suitable platform may be used, for example, platforms that support the functions defined in standards such as MPI and MPI-2.

An embodiment of the present disclosure uses middleware **1006** such as HPCM (High Performance Computing Mobility) to preserve a local process execution state and maintain active disk Input/Output (I/O) channels. Typically, other process migration or checkpointing middleware **1006** can also be utilized so long as it preserves local process state at a kernel level or a user level. Middleware **1006** may be customized to different scenarios on heterogeneous and homogeneous platforms and may perform efficiently. External runtime system **1004** may monitor the status of processes and evaluate when and where to migrate a process when it detects an imminent failure. In an embodiment, external runtime system **1004** and middleware **1006** are not built-in components of system **1000**.

Referring to FIGS. **11**, **12**, and **13**, experimental results are shown. In order to verify the practical feasibility, effectiveness, and scalability of a distributed migration protocol **400**, a collective synchronization protocol **600**, and a point-to-point synchronization protocol **800**, the MPI-Mitten library has been implemented and tested on the SunWulf Computer Farm in the Scalable Computing Software (SCS) laboratory at the Illinois Institute of Technology.

Two typical MPI benchmarks were selected for testing. The first was the IS benchmark from NAS Parallel Benchmark 3.1; the other was Mpptest. The NAS IS benchmark tests an integer sorting operation. It fills a vector with random integers, and then computes a rank for each number. The NAS IS benchmark features significant data communication, especially collective communication, and is used to test the effectiveness of the protocols as well as the normal execution overhead. Mpptest is a program that measures the performance of some MPI message passing routines in a variety of situations. It is a communication-intensive benchmark that tests the communication performance of distributed-memory parallel supercomputers (MPP's).

The system overhead was first tested during normal execution with no failures detected and therefore no migration taking place. FIG. **11** is an example graphical illustration of MPI-Mitten overhead for the NAS IS benchmark and for the Mpptest benchmark. Because the NAS IS and the Mpptest benchmarks contain many collective operations, the experiment results for these benchmarks represent an example of a worst case scenario. The tests were performed for data sizes from A to C where C was the maximum problem size. The tests were performed on 2 to 64 processes. The overall overhead was less than 4% and the average overhead was 1.22% for NAS IS and 3.55% for Mpptest. The overhead was caused by the "test" operations and synchronization operations before and after communication primitives. Because the migration signal is sent via asynchronous communication primitives, this operation does not introduce much overhead.

FIG. **12** is an example graphical illustration of the efficiency and scalability of dynamic process migration of an embodiment of the present disclosure for the NAS IS benchmark. Similarly, FIG. **13** is an example graphical illustration of the efficiency and scalability of dynamic migration of an embodiment of the present disclosure for the Mpptest benchmark. The NAS IS benchmark and Mpptest were run with 2 to 32 processes, and the example results show that the synchronization time is almost constant while the number of processes increases. The average synchronization time was 2.21 seconds for NAS IS and 2.42 for Mpptest. When the processes were increased to 32, the problem partition size decreased, so the total dynamic process migration cost also decreased. The dynamic group membership management time increased slowly because more time was spent on the initiation of a new process at the destination device. This experiment demonstrates that spawning a new process and new process initiation contribute 69.3% to 81.8% of the dynamic group membership management cost. Therefore, the dynamic group membership management cost depends on the implementation of the MPI platform. Optimizing the MPI process initialization may improve the dynamic group membership management performance.

The following publication, the entire content of which is incorporated herein by reference, includes further information regarding migration technology including MPI-Mitten: Cong Du, Xian-He Sun, "MPI-Mitten: Enabling Migration Technology in MPI," CCGRID, pp. 11-18, Sixth IEEE International Symposium on Cluster Computing and the Grid (CCGRID 06), May 16, 2006.

In summary, persons of ordinary skill in the art will readily appreciate that systems, methods and protocols for dynamic group communication have been provided. The foregoing description has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the exemplary embodiments disclosed. Many modifications and variations are possible in light of the above teachings. It is intended that the scope of the invention not be limited by this detailed description of examples.

The invention is claimed as follows:

1. A system for dynamic group communication, the system comprising:

a network;

a first computing device executing a first computing process;

a second computing device executing a second computing process;

a third computing device executing a third computing process;

the first computing process, the second computing process, and the third computing process communicating via the network, wherein the first computing process, the second computing process, and the third computing process form a first group;

the first computing process, the second computing process, and the third computing process communicating within the first group using a protocol, the protocol enabling the first computing process to migrate via the network from the first computing device to at least one of the second computing device and a fourth computing device by:

obtaining group membership information for the first group of computing processes, the group membership information pertaining to at least the first computing process, the second computing process, and the third computing process in the first group, wherein the first computing process is located on the first computing device;

waiting for a migration signal asynchronously at the first group;

receiving the migration signal asynchronously at the first computing process;

sending the migration signal asynchronously from the first computing process to at least one of the second computing process and the third computing process;

establishing a synchronization point collectively within the first group;

operating asynchronously until the first group reaches the synchronization point;

ensuring that the first group reaches the synchronization point;

spawning a fourth computing process by the first group on at least one of the second computing device and the fourth computing device, the fourth computing process replacing the first computing process in operation;

establishing a second group of computing processes, the second group including the second computing process, the third computing process, and the fourth computing process, the second group replacing the first group in operation; and

maintaining group membership information for the second group, the group membership information pertaining to at least the second computing process, the third computing process, and the fourth computing process; and the protocol enabling the first computing process, the second computing process, and the third computing process to asynchronously exchange data while the first computing process migrates.

2. The system of claim **1**, wherein the protocol enables the first computing process and the second computing process to communicate using point-to-point communication while the first computing process migrates from the first computing device to the second computing device.

3. The system of claim **1**, wherein the protocol enables the first computing process and the third computing process to communicate using point-to-point communication while the first computing process migrates from the first computing device to the second computing device.

4. The system of claim **1**, wherein the protocol enables the first computing process and the second computing process to communicate using point-to-point communication while the first computing process migrates from the first computing device to the fourth computing device.

5. The system of claim **1**, wherein the protocol enables the first computing process and the second computing process to communicate using collective communication while the first computing process migrates from the first computing device to the second computing device.

6. The system of claim **1**, wherein the protocol enables the first computing process and the third computing process to communicate using collective communication while the first computing process migrates from the first computing device to the second computing device.

7. The system of claim **1**, wherein the protocol enables the first computing process and the second computing process to communicate using collective communication while the first computing process migrates from the first computing device to the fourth computing device.

8. The system of claim **1**, wherein at least one of the first computing device, the second computing device, and the computing third device stores information for the first computing process, the second computing process, and the third computing process, the information stored according to the protocol.

9. The system of claim **8**, wherein the information is used to manage group membership according to the protocol.

10. The system of claim **1**, wherein the first computing device, the second computing device, and the third computing device select the network from a homogeneous network and a heterogeneous network.

11. The system of claim **1**, wherein the first computing process, the second computing process, and the third computing process to asynchronously exchange data while the first computing process, the second computing process, and the third computing process synchronize.

12. A method for dynamic process migration and dynamic group membership management, the method comprising:

obtaining group membership information for a first group of computing processes, the group membership information pertaining to at least a first computing process, a second computing process, and a third computing process in the first group, wherein the first computing process is located on a first computing device;

waiting for a migration signal asynchronously at the first group;

receiving the migration signal asynchronously at the first computing process;

sending the migration signal asynchronously from the first computing process to at least one of the second computing process and the third computing process;

establishing a synchronization point collectively within the first group;

operating asynchronously until the first group reaches the synchronization point;

ensuring that the first group reaches the synchronization point;

spawning a fourth computing process by the first group on a second computing device, the fourth computing process replacing the first computing process in operation;

establishing a second group of computing processes, the second group including the second computing process, the third computing process, and the fourth computing process, the second group replacing the first group in operation; and

maintaining group membership information for the second group, the group membership information pertaining to at least the second computing process, the third computing process, and the fourth computing process.

13. The method of claim **12**, wherein obtaining group membership information for the first group includes creating a one-sided communication window for the first computing process to provide group membership information comprising the IP address of the first computing device.

14. The method of claim **12**, wherein the first computing process receives the migration signal from an external runtime system.

15. The method of claim **12**, wherein the first computing process receives the migration signal internally from the first computing process.

16. The method of claim **12**, wherein establishing a synchronization point requires the second computing process and the third computing process to approve the process migration of the first computing process.

17. The method of claim **12**, wherein the first computing process, the second computing process, and the third computing process operate asynchronously using point-to-point communication until the synchronization point is reached.

18. The method of claim **12**, wherein the first computing process, the second computing process, and the third computing process operate asynchronously using collective communication until the synchronization point is reached.

19. The method of claim **12**, wherein ensuring the first group reaches the synchronization point, comprises:

determining a global superstep at the first computing process;

transmitting the global superstep to at least one of the second computing process and the third computing process;

waiting for the first group to asynchronously reach the global superstep;

using point-to-point communication to ensure that the second computing process and the third computing process are awake after the first group reaches the global superstep.

20. The method of claim **12**, wherein the first group collectively reaches a consensus to spawn the fourth process on the second device.

21. The method of claim **12**, wherein group membership information comprises the local communication state.

22. A non-transitory computer readable medium storing instructions for implementing a protocol for dynamic process migration and dynamic group membership management comprising:

a first set of instructions which enables a first computing process in a first group of computing processes to asynchronously receive a migration signal, wherein the first group is comprised of at least a first computing process, a second computing process, and a third computing process, wherein the first computing process is located on a first computing device;

a second set of instructions which causes the migration signal to be distributed to each computing process in the first group, wherein the first group is enabled to asynchronously exchange data while the second set of instructions is executed;

a third set of instructions which causes the group to collectively establish a global superstep, wherein the first group is enabled to asynchronously exchange data while the third set of instructions is executed;

a fourth set of instructions which causes each process in the first group to reach the global superstep, wherein the first group is enabled to asynchronously exchange data while the fourth set of instructions is executed;

a fifth set of instructions which ensures that each computing process in the first group reaches a synchronization point, wherein the first group is enabled to asynchronously exchange data while the fifth set of instructions is executed;

a sixth set of instructions which causes the first group to spawn a fourth computing process, wherein the fourth computing process is located on a second device;

a seventh set of instructions which causes the first group to create a second group of computing processes and maintain group membership information for the second group; and

an eighth set of instructions which causes the fourth computing process to replace the first computing process, wherein the second group is enabled to asynchronously exchange data while the eighth set of instructions is executed.

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