Low-Cost Checkpointing and Failure Recovery in Mobile Computing Systems

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Abstract—A mobile computing system consists of mobile and stationary nodes, connected to each other by a communication network. The presence of mobile nodes in the system places constraints on the permissible energy consumption and available communication bandwidth. To minimize the lost computation during recovery from node failures, periodic collection of a consistent snapshot of the system (checkpoint) is required. Locating mobile nodes contributes to the checkpointing and recovery costs. Synchronous snapshot collection algorithms, designed for static networks, either force every node in the system to take a new local snapshot, or block the underlying computation during snapshot collection. Hence, they are not suitable for mobile computing systems. If nodes take their local checkpoints independently in an uncoordinated manner, each node may have to store multiple local checkpoints in stable storage. This is not suitable for mobile nodes as they have small memory. This paper presents a synchronous snapshot collection algorithm for mobile systems that neither forces every node to take a local snapshot, nor blocks the underlying computation during snapshot collection. If a node initiates snapshot collection, local snapshots of only those nodes that have directly or transitively affected the initiator since their last snapshots need to be taken. We prove that the global snapshot collection terminates within a finite time of its invocation and the collected global snapshot is consistent. We also propose a minimal rollback/recovery algorithm in which the computation at a node is rolled back only if it depends on operations that have been undone due to the failure of node(s). Both the algorithms have low communication and storage overheads and meet the low energy consumption and low bandwidth constraints of mobile computing systems.

Index Terms—Checkpointing, causal dependency, global snapshot, mobile computing systems, portable computers, recovery.

1 Introduction

A mobile computing system is a distributed system where some of nodes are mobile computers [3]. The location of mobile computers in the network may change with time. The fixed nodes in the system are connected by a static network. A mobile node communicates with the other nodes in the system through a fixed node to which it is connected. The nodes have no common clock and no shared memory among them. They communicate with each other through messages. Each node operates independently of the others, with occasional asynchronous message communication.

In this paper, we concentrate on the checkpointing and recovery aspects of mobile computing systems. In synchronous checkpointing algorithms, a consistent snapshot of the system (also called a checkpoint) is maintained at all times. In asynchronous algorithms, the constituent nodes take their local snapshots independently, and a local snapshot is selected for each node to construct a consistent snapshot of the system at the time of recovery. A consistent global snapshot indicates a *possible* state of the system if the local states of all the nodes and the messages in transit along all the channels are recorded simultaneously. In a consistent global snapshot, the reception of a message is recorded by a node only if the corresponding send has been recorded. If a node fails, the system is rolled back to the latest consistent global snapshot [13], [20], [22], [25], [26], and then the computation proceeds from that point onwards.

To minimize the lost computation during recovery from node failures, periodic collection of a consistent snapshot of the system to advance the checkpoint is required. Thus, collection of a consistent snapshot of a mobile system is an important issue in the recovery from node failures. A good snapshot collection algorithm should be *nonintrusive* and *efficient*. A nonintrusive algorithm does not force the nodes in the system to freeze their computations during snapshot collection. An efficient algorithm keeps the effort required for collecting a consistent snapshot to a minimum. This can be achieved by forcing a minimal subset of nodes to take their local snapshots, and by employing data structures that impose low memory overheads. Consistent snapshot collection algorithms for static distributed systems have been proposed in [5], [7], [8], [13], [14], [16], [17], [18]. The snapshot collection algorithm by Chandy and Lamport [7] forces every node to take its local snapshot. The underlying computation is allowed to proceed while the global snapshot is being collected. Snapshot collection algorithms in [8], [14], [17], [18] also force every node to take its snapshot. In Koo and Toueg's algorithm [13], all the nodes are not forced to take their local snapshots. However, the underlying computation is suspended during snapshot collection. This imposes high run-time overheads on the system. Manetho [8] employs a snapshot algorithm similar to Koo and Toueg's without suspending the underlying computation. However,

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all the nodes are forced to take their local snapshots. In [5], [22], each node takes local checkpoints independently. Therefore, a node may have to store multiple local checkpoints and the recovery time may be large.

The mobility of nodes in the system raises some new issues pertinent to the design of checkpointing and recovery algorithms: locating nodes that have to take their snapshots, energy consumption constrains, and low available bandwidth for communication with the mobile nodes. We propose a new synchronous snapshot collection algorithm that accounts for the mobility of the nodes and addresses these issues. The algorithm forces a minimal set of nodes to take their snapshots, and the underlying computation is not suspended during snapshot collection. As a result, the algorithm is nonintrusive as well as efficient. It imposes low run-time overheads on the memory and the communication network. An interesting aspect of the algorithm is that it has a *lazy phase* that enables nodes to take local snapshots in a quasi-asynchronous fashion, after the coordinated snapshot collection phase (the *aggressive phase*) is over. This further reduces the amount of computation that is rolled back during recovery from node failures. Moreover, the *lazy phase* advances the checkpoint slowly, rather than in a burst. This avoids contention for the low bandwidth channels.

In previous recovery algorithms for static distributed systems, such as [20], the computation at *all* the nodes is rolled back to a mutually consistent state during recovery. In [8], [25], no nonfaulty node is made to roll back its computation. However, [25] requires extensive logging of message contents, at sender as well as receiver ends. In [8], the antecedence graph, containing the entire causal relationship, is kept in volatile storage and periodically copied to stable storage. Each computation message has to carry portions of the antecedence graph, significantly increasing the size of the messages. This can be justified for systems where node rollbacks are very expensive or are impossible (i.e., real-time systems). These mechanisms require large storage at the nodes and high bandwidth channels, both of which are in conflict with the low available bandwidth and low energy consumption requirements of mobile computing systems. We propose a recovery algorithm that requires a minimal number of nodes to undo their computations on node failures and has modest memory and communication overheads. The algorithm also copes with the changing topology of the network due to the mobility of the nodes.

The key to both the algorithms is the internode dependencies created by messages. Specifically, message communication leads to the establishment of a dependency from the sender to the receiver of the message. The inter node dependencies considered in the rest of the paper capture the *happened before* relationship described in [15]. During a snapshot collection, only the nodes from which there is a dependency onto the snapshot initiator, either direct or transitive, since their last checkpoints, are made to take their snapshots. The snapshot collection terminates within a finite time of its invocation and the global snapshot thus collected is proved to be consistent. During recovery, only those nodes whose states are dependent on the undone operations of the failed node are made to roll back.

The rest of the paper is organized as follows: Section 2 presents the system model. In Section 3, we discuss the issues pertinent to snapshot collection of mobile computing systems, and data structures required to keep track of the minimal dependency information at each node. Section 4 presents a nonblocking distributed snapshot collection algorithm. Section 5 presents a strategy to recover from node failures. Section 6 compares the proposed algorithms with the existing algorithms. Finally, Section 7 presents conclusions.

2 System Model

The system is composed of a set of n nodes, and a network of communication links connecting the nodes. Some of the nodes may change their location with time. They will be referred to as *mobile hosts* or *MH* [1], [3]. The static nodes (henceforth, referred to as mobile support stations or *MSS* [1], [3]) are connected to each other by a static network. An *MH* can be directly connected to at most one *MSS* at any given time and can communicate with other *MH*s and *MSS*s only through the *MSS* to which it is directly connected. The links in the static network support FIFO message communication. As long as an *MH* is connected to an *MSS*, the channel between them also ensures FIFO communication in both the directions. Message transmission through these links takes an unpredictable, but finite amount of time. During normal operation, no messages are lost or modified in transit. The system does not have any shared memory or a global clock. Hence, all communication and synchronization takes place through messages.

A distributed application consists of processes that communicate asynchronously with each other. These processes run on different nodes of the mobile system. The processes exchange information with each other through messages. For the application to run successfully, all the nodes on which the modules of the application are running should function properly. Node failures in the system are assumed to be fail-stop in nature. Henceforth, the term *node* will be used for both *MH*s and *MSS*s, unless explicitly stated otherwise.

The messages generated by the underlying distributed application will be referred to as the *computation messages*. Messages generated by the nodes to advance checkpoints, handle failures, and for recovery will be referred to as the *system messages*. Also, when a message of either type reaches a node, the node has the ability to peek at the message contents before actually processing it. Hence the reception/arrival of a message and its processing by the receiving node may not necessarily happen at the same time. They are two distinct events. The arrival of a message is recorded only on its processing.

3 Issues and Basic Idea

Two major objectives in the design of a snapshot collection algorithm are efficiency and nonintrusiveness. A nonintrusive algorithm does not suspend the computation at the participating nodes during snapshot collection. Therefore, new inter-node dependencies may be created while global snapshot collection is in progress, which may lead to inconsistencies if not properly handled. An efficient algorithm

forces a minimal set of nodes to take their local snapshots for each snapshot initiation, based on inter-node dependencies created since the last snapshot collection. As a result, the run-time overheads and the storage and communication overheads are kept low. A consequence of the efficiency and nonintrusiveness criteria is that the snapshot initiator does not know *a priori* the identity of all the nodes that will participate in the snapshot collection. This raises the issue of efficient termination detection of the snapshot collection process.

3.1 Issues

The mobility and energy consumption of the mobile hosts raise issues not faced in a static distributed system.

3.1.1 Mobility

Changes in the location of an *MH* complicate the routing of messages. Messages sent by a node to another node may have to be rerouted because the destination node (*MH*) disconnected from the old *MSS* and is now connected to a new *MSS*. An *MH* may be disconnected from the network for a finite, but arbitrary period of time while switching from the old *MSS* to the new *MSS*. Routing protocols for the network layer, to handle node mobility, have been proposed in [2], [4], [12], [23], [27].

At the applications level, the checkpointing algorithm may generate a request for the disconnected *MH* to take its snapshot. Delaying a response to such a request, until the *MH* reconnects with some *MSS*, may significantly increase the completion time of the snapshot collection algorithm. So, an alternative solution is needed. One such solution is presented in Section 3.3.

There may be instances where the *MH* leaves the network, never to reconnect with it again. In such situations, it must be ensured that all the computations in which the *MH* is involved terminate before the *MH* quits the network.

3.1.2 Energy Consumption

An *MH* is usually powered by a stand alone energy source, like a battery pack, that has to be replenished after a certain period of time. The mobility of an *MH* is directly dependent on its energy efficiency. The various components like the CPU, display, disk drive, etc. drain the battery. Message transmission and reception also consume energy. Energy consumption can be reduced by powering down individual components during periods of low activity [10]. This strategy is referred to as the *doze mode* operation [3].

Energy can be conserved during snapshot collection by forcing a minimal set of nodes to take their local snapshots. Otherwise, some *MH*s that have been dozing will be waken up by the snapshot collection. These *MH*s may not have participated in any computation for an extended period of time, and a new local snapshot of such *MH*s may not be required to create a consistent snapshot. Energy conservation and low bandwidth constraints are satisfied by reducing the number of system messages required to collect a consistent snapshot.

3.2 Minimal Dependency Information

Causal relationships are established through messages. Node P_i maintains a Boolean vector, R_i, of n components. At P_i, the vector is initialized as follows:

- $R_i[i] = 1$;
- $R_i[j] = 0$ if $j \neq i$;

When node P_i sends a message to P_j, it appends R_i to the message. This informs P_j about the nodes that have causally affected P_i. While processing a message m, P_j extracts the Boolean vector $m.R$ from the message and uses it to update R_j as follows: $R_j[k] \leftarrow R_j[k] \vee m.R[k]$, where $1 \leq k \leq n$. The processing of a message and the update of vector R_j take place as an atomic operation. This operation updates the dependency information. If the sender of a message is dependent on a node P_k before sending the message, the receiver will also be dependent on P_k on receiving the message. The spread of dependency information through messages is illustrated in Fig. 1. P_4 is dependent on P_2 after receiving m_3. Since P_2 was dependent on P_1 before sending m_3, P_4 becomes (transitively) dependent on P_1 on receiving m_3.

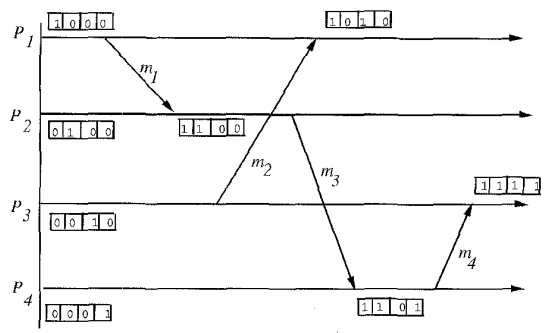

Fig. 1. Propagation of dependency information.

Fidge [9] and Mattern [17] proposed vector clocks to maintain causality information. However, the overheads associated with vector clocks are high because a vector of n integers is sent with each message. Assuming that each integer is stored in a 32-bit word, an n node system would have at least $4n$ bytes of overhead per message. As the word sizes of machines grow in the future, the overhead will also grow. This overhead can be quite debilitating for mobile systems because the links between *MH – MSS* pairs are usually low bandwidth wireless links. In comparison, the dependency vector only needs n bits of storage, and is independent of changes in the machine word size. Also, each update of the vector clock at a node, on receiving a message, requires up to n integer comparisons, as opposed to n bit-wise OR operations for the dependency vector. The bit operations are much faster than integer operations.

The use of the dependency information reduces the effort required to collect a global snapshot, as illustrated by the example in Fig. 2. The vertical line S_1 represents the global snapshot at the beginning of the computation. Later, when P_2 initiates a new snapshot collection (at the instant marked by "X" on its time line), only P_3 and P_4 need to take their local snapshots because there are dependencies from these nodes onto P_2. Nodes P_1 and P_5 need not take their snapshots because they do not have dependencies onto P_2. The new global snapshot is represented by the cut S_2.

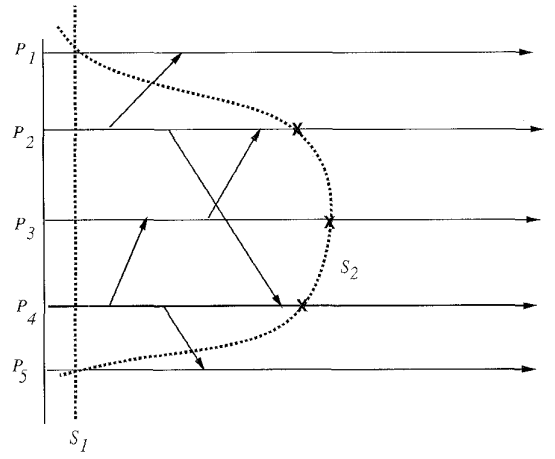

Fig. 2. Local snapshots of minimal number of nodes taken.

3.3 Handling Node Mobility

Let a mobile host MH_i be initially connected to MSS_p. Then it disconnects from MSS_p and after a finite period of time connects with MSS_q. During the disconnect interval, only local events can take place at MH_i. No message send or receive events occur during this interval. Hence, no new dependencies with respect to other nodes are created during this interval. The dependency relation of MH_i with the rest of the system, as reflected by its local snapshot, is the same no matter when the local snapshot is taken during the disconnect interval.

Disconnection of a mobile host from an MSS: At the time of disconnecting from MSS_p, MH_i takes its local snapshot which is stored at MSS_p as *disconnect_snapshot*$_i$. REQUESTs arriving at MSS_p to take MH_i's snapshot during the disconnect interval are serviced by using *disconnect_snapshot*$_i$ as MH_i's local snapshot. The dependency vector of MH_i (R_i) at the time of taking the snapshot is used to propagate the snapshot request. Computation messages, meant for MH_i, arriving at MSS_p during the disconnect interval are buffered at MSS_p until the end of the interval.

Reconnection of a mobile host to an MSS: The disconnect interval ends when MH_i connects to MSS_q and executes a *reconnect routine*. We assume that MH_i keeps in its stable storage the identity of the last *MSS* it was connected to (MSS_p). On connecting with MSS_q, the reconnect routine sends a query, through MSS_q, to MSS_p. If MH_i's stable storage does not contain the identity of its last *MSS* for some reason, then the query is broadcast over the network. On receiving the query, MSS_p executes the following steps: if MSS_p had processed a snapshot request for MH_i during the disconnect interval, the corresponding snapshot (*disconnect_snapshot*$_i$) and the buffered messages are sent to MH_i. If no snapshot request for MH_i was received by MSS_p during the disconnect interval, only the buffered messages are sent. Having sent the messages (and *disconnect_snapshot*$_i$ if a snapshot request was processed), MSS_p discards the buffered messages, *disconnect_snapshot*$_i$, and the dependency vector of MH_i. When the data sent by MSS_p (buffered messages and possibly *disconnect_snapshot*$_i$) arrives at MH_i, MH_i executes the following actions: If the received data contains *disconnect_snapshot*$_i$, MH_i stores this snapshot as its local snapshot, and resets all except the ith component of the dependency vector, R_i, before processing the messages. Then, all the buffered messages received from MSS_p are processed, and the dependency vector is modified to reflect the reception of these messages. With this the reconnect routine terminates and the relocated mobile node MH_i can resume normal communication with other nodes in the system. As the old *MSS* discards the *disconnect_snapshot*$_i$ at the end of the disconnect interval, an *MH* will not leave its local checkpoints at various *MSS*s in the fixed network.

Thus, the operations carried out by the *MH* and old *MSS* during the disconnect interval, and by the new and old *MSS*s and the *MH* during the reconnect routine hide the mobility of the *MH* from all the other nodes in the system.

Optimizations: When an *MH* disconnects from an *MSS*, its state at the time of disconnection is available at the old *MSS*. So, instead of simply buffering the incoming messages for the *MH*, it is possible for the old *MSS* to process these messages on behalf of the disconnected *MH*. Variables, local to the *MH*, may be modified at the old *MSS* due to the reception of the messages. However, the local events at the disconnected *MH* may also modify the same variables. These modifications are being made to two different copies of the variables. It may be difficult to reconcile the inconsistencies that may arise due to these independent and concurrent modifications to the same variables. So this alternative is not very appealing. Postponing the processing of the messages meant for the *MH*, received during the disconnect interval, until the reconnect routine is executed, is equivalent to adding the duration of postponement to the message propagation time. Assuming that the disconnect interval is finite, the postponement does not violate the assumption that message propagation time is finite but unpredictable.

In the reconnect routine as described above, MSS_p sends *disconnect_snapshot*$_i$ to MH_i if MSS_p has processed a snapshot request for MH_i during the disconnect interval. Alternatively, MSS_p can ask the relocated MH_i to take a new local snapshot before processing the buffered messages. The consistency of a global snapshot remains unaffected as *disconnect_snapshot*$_i$ and the new local snapshot of MH_i reflect the same dependency relation with respect to the rest of the system, and can be substituted for one another. Moreover, precious bandwidth that would have been used to send *disconnect_snapshot*$_i$ during the reconnect routine is saved. However, this alternative is not suitable under all circumstances. Let us assume that a global snapshot is being collected to evaluate a predicate. During the snapshot collection, *disconnect_snapshot*$_i$ is used as MH_i's local snapshot, and the predicate returns a certain value. The local events at MH_i during the disconnect interval may modify some local variables which will be reflected in the new local snapshot of MH_i taken during the reconnect routine. Later, if the predicate is evaluated for the same global snapshot after MH_i has connected to MSS_q, it may return a different value. The same system state may appear to be returning different

values for a predicate. The alternative described here can be employed if the local events at MH_i during the disconnect interval do not modify the variables on which the value of the predicate is dependent, or if the predicate being evaluated is a *stable predicate* and was true at the time of disconnection of MH_i.

Section 4 presents an algorithm to collect the snapshot of a mobile distributed system. It addresses the issues raised in Section 3.1, and is more efficient than the snapshot collection algorithms for static distributed systems proposed in the past. In the algorithm, no distinction is made between mobile and static nodes as the mobility of nodes can be hidden as described above.

4 Minimal Snapshot Collection Algorithm

In this section, we present a nonblocking snapshot collection algorithm for mobile computing systems. The algorithm forces a minimal set of nodes to take their local snapshots. Thus the effort required for snapshot collection is reduced, and nodes that have been dozing are unlikely to be disturbed. Moreover, the algorithm is nonintrusive.

After the coordinated snapshot collection terminates, the nodes that did not participate in the snapshot collection can take their local snapshots in a quasi-asynchronous fashion. This reduces the amount of computation that has to be undone on node failures. Huang's algorithm [11] is employed to detect the termination of the coordinated snapshot collection. Unlike [6], [13], information about termination is not propagated along a tree rooted at the snapshot initiator. Instead, the nodes send this information directly to the initiator. Hence, termination detection is fast and inexpensive.

In [13], if multiple coordinated snapshot collections are initiated concurrently, all of them may have to be aborted in some situations. This will lead to wastage of effort. In [21], such concurrent initiations are handled by restricting the propagation of snapshot requests in the system. Each concurrent initiation collects state information about a subset of the nodes. This information is then pooled together to construct a global snapshot. We assume that at any time, at most one snapshot collection is in progress. Techniques to handle concurrent initiations of snapshot collection by multiple nodes have been presented in [19]. As multiple concurrent initiations of snapshot collection is orthogonal to our discussion, we only briefly mention the main features of [19]. When a node receives its first request for snapshot collection initiated by another node, it takes its local snapshot and propagates the request to neighboring nodes. All the local snapshots taken by the participating nodes for a snapshot initiation collectively form a global snapshot. The state information collected by each independent global snapshot collection is combined. The combination is driven by the fact that the union of consistent global snapshots is also a consistent global snapshot. The snapshot thus generated is more recent than each of the snapshots collected independently, and also more recent than that collected by [21]. Therefore, the amount of computation lost during rollback, after node failures, is minimized. The underlying computation does not have to be suspended during snapshot collection.

4.1 Data Structures

Besides the Boolean vector R_i described in Section 3.2, each node maintains the following data structures:

interval_number: an integer value maintained at each node that is incremented each time the node takes its local snapshot.

interval_vector: an array of n integers at each node, where interval_vector[j] indicates the interval_number of the next message expected from node P_j. For node P_i, interval_vector[i] is equal to its interval_number.

trigger: a tuple (*pid*, *inum*) maintained by each node. *pid* indicates the snapshot initiator that triggered this node to take its latest checkpoint. *inum* indicates the interval_number at node *pid* when it took its own local snapshot on initiating the snapshot collection. *trigger* is appended to every system message and the first computation message that a node sends to every other node after taking a local snapshot.

send_infect: a Boolean vector of size n maintained by each node in its stable storage. The vector is initialized to all zeroes each time a snapshot at that node is taken. When a node P_i sends a computation message to node P_j, it sets send_infect[j] to 1. Thus this vector indicates the nodes to which computation messages have been sent since the last checkpoint, or since the beginning of the computation whichever is later.

propagate: a Boolean vector of size n maintained by each node in its stable storage. It is used to keep track of the nodes to which snapshot REQUESTs were sent by the node. The vector is initialized to all 0s.

weight: a nonnegative variable of type *real* with maximum value of 1. It is used to detect the termination of the snapshot collection.

The interval_numbers and interval_vectors are initialized to 1 and an array of 1s, respectively, at all the nodes. The trigger tuple at node P_i is initialized to (i, 1). The weight at a node is initialized to 0.

When node P_i sends any message, it appends its interval_number and the dependency vector, R_i, to the message.

4.2 The Algorithm

Snapshot initiation: The algorithm does not require any node to suspend its underlying computation. When P_i initiates a snapshot collection, it takes a tentative local snapshot, increments its interval_number, sets *weight* to 1, and stores its own identifier and the new interval_number in trigger. It then sends snapshot REQUESTs to all the nodes P_j, such that $R_i[j] = 1$ and resumes its computation. Each REQUEST message carries the trigger of the initiating node, the vector R_i and a portion of the weight. The weight of the REQUEST sender is decreased by an equal amount.

Reception of snapshot REQUEST: When a snapshot REQUEST is received by a node P_i and *request.trigger* is not equal to P_i.*trigger*, P_i takes a tentative local snapshot and sends REQUESTs to all the nodes that have their corresponding bits set in its dependency vector, R_i, but not in the vector $m.R$ carried by the received REQUEST. Also, when P_i REQUESTs another node to take its snapshot on behalf of the initiator, it appends the initiator's trigger tuple

and a portion of the received weight to all those REQUESTs. P_i then sends a RESPONSE to the initiator with the remaining weight and resumes its underlying computation. As already explained in Section 3.3, if P_i is an *MH* and the REQUESTs are generated during its disconnect interval, then the operations described above are carried out on its behalf by the *MSS* to which it was previously connected.

If *request.trigger* is equal to P_i.*trigger* when P_i receives the REQUEST (implying that P_i has already taken its snapshot for this snapshot initiation), P_i does not take a local snapshot. But,

- if the *propagate* vector has no 1s in it, then a RESPONSE is sent to the snapshot initiator with a weight equal to the weight received in the REQUEST.
- if the *propagate* vector has some bits set to 1, then for all j such that *propagate*[j] = 1, a REQUEST is sent to P_j with a nonzero portion of the weight received in the REQUEST. Then the *propagate* vector is reset to all 0s and the remaining portion of the received weight is sent to the initiator in a RESPONSE.

The bits in the *propagate* vector are set when REQUESTs are sent to nodes on the reception of computation messages as described later in this section. Note that the trigger carried by the REQUEST messages prevents a node from taking multiple snapshots when the node receives multiple REQUESTs for the same global snapshot initiation.

Computation messages received during snapshot collection: Since the computation at any node does not block after it has taken a snapshot, the following scenario is possible: A node P_j takes its snapshot and then sends a computation message m to node P_k. Node P_k receives (and processes) this message before it receives a REQUEST messages to take its snapshot. This will lead to an inconsistency in the global snapshot—the snapshot taken by P_k will be causally dependent upon the snapshot of P_j. This problem is solved by having a node include its trigger in the first computation message it sends to every other node after taking its snapshot. P_j checks if *send_infect*[k] = 0 before sending a computation message to P_k. If so, it sets *send_infect*[k] to 1 and appends its trigger to the message. When P_k receives this message from P_j, by looking at the trigger in the message, P_k can infer that P_j has taken a new snapshot before sending the message. Consequently, P_k takes its tentative snapshot before processing the message. Later, if P_k receives a REQUEST message for the snapshot initiation, it knows that a local snapshot has already been taken (the local trigger is equal to the trigger in the message).

When P_j receives a computation message m from P_i, it compares the interval_number received in the message with its own interval_vector[i]. If the interval_number received is less than or equal to interval_vector[i], then the message is processed and no snapshot is taken. If the interval_number of the computation message received is greater than interval_vector[i], it implies that P_i took a snapshot before sending the message, and this message is the first computation message sent by P_i to P_j since P_i's snapshot. So, the message must have a trigger tuple. The following steps are executed in such a situation:

1) P_j's interval_vector[i] is updated to the interval_number in the message received from P_i.
2) P_j checks the trigger tuple of the message received. For the sake of convenience, we shall call the trigger tuple at P_j as *own_trigger* while the trigger tuple received in the message as *msg_trigger*.
   a) if *msg_trigger* = *own_trigger*, it means that the latest snapshots of P_i and P_j were both taken in response to the same snapshot initiation event. So no action needs to be taken besides updating the dependency vector, R_j.
   b) if *msg_trigger.pid* = *own_trigger.pid* $\wedge$ *msg_trigger.inum* > *own_trigger.inum*, it means that P_i has sent the message after taking a new snapshot, while P_j has not taken a snapshot for this snapshot initiation. So P_j takes a tentative snapshot before processing the message and the tuple *own_trigger* is set to be equal to *msg_trigger*. P_j also propagates the snapshot request by sending REQUESTs to all the nodes that have their corresponding bits set in R_j, but not in the bit-vector $m.R$ of the message received. For every such REQUEST message sent out to node P_k, *propagate*[k] is set to 1.
   c) if *msg_trigger.pid* $\neq$ *own_trigger.pid*, there are two possibilities:
      i) if P_j has not processed any message satisfying the condition *msg_trigger.pid* $\neq$ *own_trigger.pid* since its last local snapshot, then P_j takes its tentative snapshot and sets *own_trigger* to *msg_trigger* before processing the message. Then P_j propagates the snapshot REQUEST, using the dependency vector R_j, as described in case (b).
      ii) if P_j has already processed a message from any node satisfying the condition *msg_trigger.pid* $\neq$ *own_trigger.pid* since its last local snapshot, then no new local snapshot needs to be taken.

Promotion and reclamation of checkpoints: The snapshot initiator adds weights received in RESPONSEs to its own weight. When its weight becomes equal to 1, it concludes that all the nodes involved in the snapshot collection have taken their tentative local snapshots and sends out COMMIT messages to all the nodes from which it received RESPONSEs. The nodes turn their tentative snapshots into permanent ones on receiving the COMMIT message. The older permanent local snapshots at these nodes are discarded because the node will never roll back to a point prior to the newly committed checkpoint.

The pseudocode for the algorithm is presented in Fig. 3.

```
type trigger = record (pid : node_id; inum : integer;) end
var own_trigger, msg_trigger : trigger;
    interval_vector : array[1..n] of integer;
    interval_number, rfirst : integer;                weight: real;
    R_i, Propagate, Temp2, vector, first : bit vector of size n;
Actions taken when P_i sends computation message to P_j
if first[j]=0 then {first[j]←1; send(P_i, message, R_i, interval_number, own_trigger); }
          else send(P_i, message, R_i, interval_number, NULL);
Action for snapshot initiation by P_j
clear first; rfirst←0; take local snapshot; weight←1.0
own_trigger.pid←own_identifier(P_j); increment(interval_number);
own_trigger.inum←interval_number; increment(interval_vector[j]);
to all nodes P_i,such that R[i]=1
              { weight←weight/2; send_weight←weight;
                send(initiator_id, REQUEST, R_j, interval_number, own_trigger, send_weight);}
reset all bits, except own bit, in the dependency vector R_j;
resume normal computation;
Other nodes, P_i, on receiving snapshot request from P_j
receive(P_j, REQUEST, m.R, interval_number', msg_trigger, recv_weight);
if msg_trigger = own_trigger then{
   to all nodes P_k,such that Propagate[k]=1
      { recv_weight←recv_weight/2; send_weight ←recv_weight;
        send(P_i, REQUEST, R_i, interval_number, own_trigger, send_weight);}
   Propagate←all 0's;
   send(P_i, RESPONSE, recv_weight) to initiator;}
else { interval_vector[j]← interval_number';
       propagate_snapshot(R_i, m.R, P_i, interval_number, msg_trigger, recv_weight);
       Propagate←all 0's;}
resume normal computation;
Action for node P_i, on receiving computation message from P_j
receive(P_j, REQUEST, m.R, interval_number', msg_trigger);
if interval_number' ≤ interval_vector[j] then process the message and exit;
else { interval_vector[j]← interval_number';
       if msg_trigger.pid = own_trigger.pid then
          { if msg_trigger.inum = own_trigger.inum then process the message;
            else{ propagate_snapshot(R_i, m.R, P_i, interval_number, msg_trigger,0);
                  process the message; rfirst←1;} }
       else{ if rfirst = 0 then
               { propagate_snapshot(R_i, m.R, P_i, interval_number, msg_trigger,0);
                 process the message; rfirst←1;}
             else process the message;} }
propagate_snapshot(R_i, m.R, P_i, interval_number, msg_trigger, recv_weight)
{take local snapshot; rfirst←0;
 increment(interval_number); increment(interval_vector[i]);
 own_trigger←msg_trigger;
 Propagate←R_i - m.R; Temp2←R_i OR m.R;
 to all nodes P_k, such that Propagate[k]=1{
       recv_weight←recv_weight/2; send_weight ←recv_weight;
       send(P_i, REQUEST, Temp2, interval_number, own_trigger, send_weight);}
 reset all bits, except own bit, in the dependency vector R_i;
 send(P_i, RESPONSE, recv_weight) to initiator;}
```

Fig. 3. Nonblocking snapshot collection algorithm.

4.3 An Example

The operation of the algorithm can be better understood with the aid of the example presented in Fig. 4. Node P_2 initiates a snapshot collection by taking its local snapshot at the instant marked by "X." There are dependencies from P_1 and P_3 to P_2. So, REQUEST messages (indicated by broken arrows) are sent to P_1 and P_3 to take their snapshots. P_3 sends a message m_4 to P_1 after taking its snapshot. When m_4 reaches P_1, it is the first message received by P_1 such that *msg_trigger.pid* ≠ *own_trigger.pid*. So, P_1 takes its snapshot just before processing m_4.

Node P_0 that has not yet communicated with any other node, takes a local snapshot independent of any other snapshot collection process. Later, it sends a message m_5 to P_1. As a result of P_0 taking an independent local snapshot, the interval number of m_5 is higher than the value expected by P_1 from P_0. But when m_5 reaches P_1, it is not the first computation message received by P_1 with a higher interval number than expected whose *msg_trigger.pid* is different from P_1's *own_trigger.pid* since the last snapshot. So a snapshot is not taken, as explained in step 2cii (because it will lead to inconsistency—the reception of m_4 will be recorded if P_1 takes a snapshot just before it processes m_5, but the transmission of m_4 will not have been recorded by P_3). Yet another reason for not taking a new snapshot each time a computation message with a higher interval number than expected is received is that it may lead to an *avalanche effect*. For example, in Fig. 4, if a snapshot is taken before processing m_5, then P_3 will have to take another snapshot to maintain consistency. If in the meanwhile P_3 has received a message since it sent m_4, then the sender of that message has to take a snapshot. This chain may never end!

The snapshot REQUEST sent by P_2 to P_1, reaches P_1 after P_1 has taken a local snapshot on the arrival of the computation message m_4. So, *msg_trigger* (of the REQUEST) is equal to *own_trigger*. Hence, the snapshot REQUEST is ignored, as explained in part 2a of the algorithm.

4.4 Aggressive and Lazy Checkpointing

In the algorithm, only the nodes on which the initiator is dependent are *forced* to take their snapshots. During the coordinated snapshot collection, nodes are made to take their local snapshots on the arrival of REQUEST messages, or computation messages with higher than expected inter-

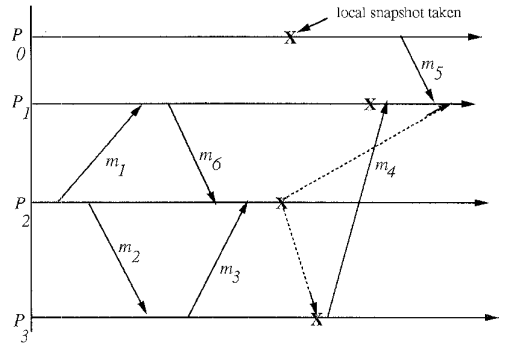

Fig. 4. An example snapshot collection.

val numbers. These snapshots are committed on the termination of the coordinated snapshot collection phase. This is called *aggressive* checkpoint advancement. Once the coordinated snapshot collection terminates, other nodes on which the initiator is not dependent (either directly or transitively) advance their checkpoints in a *lazy* fashion when they receive the first computation message with a higher than expected interval number.

For example, let the system shown in Fig. 4 have an additional node P_4. Let P_3 send a computation message to P_4 before taking its local snapshot in response to P_2's request. If P_4 has not been involved in any other communication, it will not take a snapshot for the snapshot collection initiated by P_2 (no aggressive checkpoint advancement at P_4). But, if P_3 sends yet another computation message to P_4 after taking its local snapshot, then P_4 will take its local snapshot before processing this message (advancing the checkpoint in a lazy manner). The checkpointing by nodes during the lazy phase, even though driven by message receptions, simulates a quasi-asynchronous checkpointing. So, it may not be necessary to initiate synchronous checkpointing frequently.

Lazy checkpoint advancement is especially suited for mobile computing systems. A steady advancement of the checkpoint during the lazy phase precludes the need for frequent initiations of coordinated snapshot collection. Infrequent initiations of snapshot collection cause the imposition of the high checkpointing overheads of coordinated snapshot collection on the low bandwidth network connecting *MH*s to corresponding *MSS*s only occasionally. Besides, the lazy advancement is due to transmission of computation messages. So, it imposes little overheads of its own. It also prevents the global snapshot from getting out of date. So, the amount of computation that may have to be undone during recovery from node failures is minimized.

Thus, the snapshot collection algorithm is a combination of aggressive and lazy advancements of checkpoints. When snapshots are taken on the arrival of computation messages, the higher than expected interval_number in the message has the same effect as a piggybacked snapshot REQUEST. Piggybacking control information to distinguish between messages sent by a node before and after its snapshot is a strategy used for consistent snapshot collection in systems where communication channels are non-FIFO and computation messages sent after taking a snapshot may overtake the snapshot collection marker [14]. Therefore, the proposed algorithm can be readily modified for consistent snapshot collection of systems where message communication is non-FIFO.

4.5 Handling Node Failures During Snapshot Collection

There is a possibility that during aggressive snapshot collection, nodes participating in the snapshot collection fail. We assume that if a node fails, its neighboring nodes that try to communicate with it get to know of the failure. If the failed node P_i is not the snapshot initiator, there are two cases: P_i can fail before it receives the first snapshot REQUEST for the snapshot collection, or it can fail after taking a tentative local snapshot. When a neighboring node tries to send a REQUEST to P_i and gets to know about P_i's failure, it sends an ABORT message to the snapshot initiator. On receiving an ABORT message from a node, the snapshot initiator broadcasts a DISCARD message. All the nodes that have taken a tentative snapshot for this snapshot initiation discard the tentative snapshot on receiving the DISCARD message. Later, if a node receives a REQUEST corresponding to a snapshot initiation for which a DISCARD has already been received, the REQUEST is ignored. When a previously failed node P_i restarts it may be in one of two possible states. It may have taken a tentative local snapshot before failure, or it may have failed before receiving a snapshot REQUEST. If it had taken a tentative local snapshot then it probes the corresponding snapshot initiator. If P_i discovers that the initiator had sent a COMMIT message corresponding to that initiation, it commits its tentative snapshot to a permanent one; otherwise it discards the tentative snapshot. If no tentative local snapshot was taken before failure, no probes are sent.

If the failed node was a snapshot initiator and the failure occurred before the node sent out COMMIT or DISCARD messages, on restarting after failure it broadcasts a DISCARD message corresponding to its snapshot initiation. If it had failed after broadcasting COMMIT or DISCARD messages then it does not do anything more for that snapshot initiation. The probability of a node failure during aggressive snapshot collection is low because such snapshot collection is done infrequently and it terminates in a short period of time. Moreover, the participating nodes do not have to suspend their underlying computation during snapshot collection. So, failure of the snapshot initiator *does not* hinder the underlying computation at the other nodes for the duration of the initiator's failure.

4.6 Proof of Correctness

LEMMA 1. *If node P_i takes a snapshot $\wedge$ $R_i[j] = 1$, then P_j takes a snapshot for the same snapshot initiation.*

PROOF. If node P_i initiates snapshot collection, it sends REQUESTs to all P_j such that $R_i[j] = 1$. If P_i is not the snapshot initiator and takes its snapshot on receiving a REQUEST from P_k, then for every node P_j such that $R_i[j] = 1$, there are two possibilities:

Case 1: If $m.R[j] = 0$ in the REQUEST received by P_i from P_k, then P_i sends a REQUEST to P_j.

Case 2: If $m.R[j] = 1$ in the REQUEST received by P_i from P_k,

then a REQUEST has been sent to P_j by at least one node in the snapshot REQUEST propagation path from the snapshot initiator to P_k.

So, at least one snapshot REQUEST is sent to P_j. If P_j is a static host, then the underlying network will route the REQUEST to it. If P_j is an *MH* and P_i's knowledge of P_j's location indicates that the latter is connected to MSS_p, then there are three possibilities when the REQUEST reaches MSS_p:

1) P_j is still connected to MSS_p: the REQUEST is forwarded to P_j.
2) P_j is disconnected from the network: MSS_p takes a snapshot on behalf of P_j by converting $disconnect\_snapshot_j$ into a tentative local snapshot for P_j.
3) Pj has reconnected to MSS_q: MSS_p forwards the REQUEST to MSS_q as explained in Section 3.3.

Thus, if a node takes a snapshot, every node on which it is directly dependent receives at least one snapshot REQUEST.

There are two possibilities when P_j receives the first snapshot REQUEST:

1) P_j has not taken its snapshot when the first snapshot REQUEST for this initiation arrives: P_j takes its snapshot on receiving the REQUEST message.
2) P_j has taken a snapshot for this snapshot initiation when the first snapshot REQUEST arrives: this REQUEST and all subsequent REQUESTs for this initiation are ignored. (The snapshot was taken when the first computation message with a higher than expected interval_number is received since the node's last snapshot. The msg_trigger carries the identity of the snapshot initiator.)

Hence, when a node takes a snapshot, every node on which it is directly dependent takes a snapshot. □

Applying the transitivity property of the dependence relation, we conclude that every node on which the initiator is dependent, directly or transitively, takes a snapshot. These dependencies may have been present before the snapshot collection was initiated, or may have been created while the coordinated snapshot collection (aggressive phase) was in progress.

THEOREM 1. *The algorithm ensures consistent global snapshot collection.*

PROOF. In order to prove the theorem, we have to prove that: *If the reception of a message has been recorded in the snapshot of a node, then the corresponding transmission has been recorded in the snapshot of the sender node.*

Let P_i record the reception of message m from P_j in its snapshot. So, $R_i[j] = 1$ at P_i at the time of taking its snapshot. From Lemma 1, P_j's snapshot, too, is taken. There are three possible situations under which P_j's snapshot is taken:

Case 1: P_j's snapshot is taken due to a REQUEST from P_i. Then:

send(m) at $P_j \rightarrow$ receive(m) at P_i,

where "$\rightarrow$" is the "happened before" relation described in [15]

receive(m) at $P_i \rightarrow$ snapshot taken at P_i

snapshot taken at $P_i \rightarrow$ REQUEST sent by P_i to P_j

REQUEST sent by P_i to $P_j \rightarrow$ snapshot taken at P_j

Using the transitivity property of $\rightarrow$, we have: send(m) at $P_j \rightarrow$ snapshot taken at P_j.

Thus sending of m is recorded at P_j.

Case 2: P_j's snapshot is taken due to a REQUEST from a node P_k, $k \neq i$. Let us assume that P_j sends m after taking its local snapshot implying that when m arrives at P_i, its interval_number is greater than interval_vector[j] at P_i. So, P_i takes its snapshot before processing m. Hence, reception of m is not recorded in the snapshot of P_i—a contradiction of the starting assumption that P_i had recorded the reception of the message. So, P_j must have sent m before taking its local snapshot.

Case 3: P_j's snapshot is taken due to the arrival of a computation message m' at P_j from P_k. Let us assume that m' has been received and local snapshot has been taken at P_j before P_j sends m to P_i. This is similar to Case 2, and leads to a similar contradiction. So, m' must have been received after sending m and the transmission of m must have been recorded in P_j's snapshot.

Thus, if the reception of a message is recorded in the snapshot, then its transmission must have been recorded in the snapshot. □

Lemma 2. *Aggressive snapshot collection terminates within a finite time of its initiation.*

Proof. The following invariant will be used for proving the lemma:

$$\textit{weight at the snapshot initiator} + \sum(\textit{weights at other nodes}) + \sum(\textit{weights of REQUEST and RESPONSE messages}) = 1.$$

When snapshot collection is initiated by a node P_j, initial weight of $P_j = 1$. No weight is associated with other nodes. No REQUEST or RESPONSE messages are in transit. Hence, the invariant holds.

During snapshot propagation, the initiator sends out portions of its weight in each outgoing REQUEST message. Therefore, Σ(*weight sent with each outgoing REQUEST*) + *remaining weight at* $P_j = 1$. When a node P_i receives a snapshot REQUEST, there are two possibilities:

1) If it is the first REQUEST received by Pi for this snapshot initiation:
   - part of the received weight is propagated to other nodes (those with Propagate bit = 1)
   - rest of the weight is sent in a RESPONSE to the initiator
   - the Propagate bits are cleared after sending the REQUESTs.
2) If the received REQUEST is not the first REQUEST received by P_i for this snapshot initiation:
   - REQUEST is not propagated any further because

the Propagate bits have already been cleared
- entire received weight is sent back to the initiator P_j.

Therefore, no portion of the weight in a REQUEST is retained by P_i. At any instant of time during snapshot propagation, REQUESTs and RESPONSEs may be in transit, and some noninitiator nodes may have nonzero weights. However, no extra weight is *created* or *deleted* at the noninitiator nodes. Therefore, the invariant holds.

The propagation of snapshot REQUESTs can be represented by a directed graph in which there is an edge from P_i to P_k if P_k received its first snapshot REQUEST from P_i. This graph is a tree with the initiator as the root. Since the number of nodes in the system is finite, the depth of the tree is finite. Hence, the longest path along which the initiator's REQUEST has to propagate is bounded. As message propagation time is finite, every leaf node in the tree will receive its first REQUEST for snapshot collection in finite time. As REQUEST propagation takes place only on receiving the first REQUEST for snapshot collection, the propagation stops after every leaf node has received a REQUEST message. Therefore, within a finite time of snapshot initiation no new REQUEST messages will be generated and all such messages generated in the past will be *consumed* by the receiving nodes. From this point of time onward:

$$\sum(\textit{weight contained in REQUEST messages}) = 0$$

The starting weight of 1.0 is distributed among the initiator, other nodes that have taken tentative local snapshots, and the RESPONSE messages in transit towards the initiator, i.e.,

$$\textit{weight at the snapshot initiator} + \sum(\textit{weights at noninitiator nodes}) + \sum(\textit{weight of RESPONSE messages}) = 1.$$

Since on the receipt of a REQUEST a noninitiator node immediately sends out the weight received in a REQUEST message on REQUESTs/RESPONSE, within a finite time of the end of snapshot propagation the weight of all the noninitiator nodes becomes zero. As there are no more REQUEST messages in the system, the noninitiator nodes cannot acquire any weight in the future. From this point of time onwards:

$$\sum(\textit{weight of noninitiator nodes}) = 0$$

At this point of time, the weight is distributed between the RESPONSE messages and the initiator, and *weight at the snapshot initiator* + $\sum$(*weight of RESPONSE messages*) = 1.

As message propagation time is finite, all the RESPONSEs will be received by the initiator in a finite time and their weights will be added to the initiator's weight. As there are no more REQUEST messages, no new RESPONSEs will be generated. So, in the future:

$$\sum(\textit{weight of RESPONSE messages}) = 0$$

Therefore, within a finite time of the initiation of snapshot collection, the initiator's weight becomes 1. At this point, the initiator sends COMMIT messages to the nodes that took tentative snapshots. A noninitiator node receives the COMMIT message in finite time. Therefore, aggressive snapshot collection terminates within a finite time of its initiation. □

5 Recovery from a Failure

To recover from node failures, the system should be restored to a consistent state before the computation can proceed. Failure recovery algorithms for static distributed systems have not considered the issues pertinent to mobile networks. In some of these recovery algorithms, if a node fails and has to roll back to its local checkpoint, *all* the other nodes are also rolled back to their checkpoints [20]. This is an expensive recovery method for two reasons: First, it may involve unnecessary node rollbacks. If the computation at a node P_i is not dependent on an operation that was undone due to the rollback of the failed node, then P_i should not be made to roll back. Furthermore, *MH*s that are *dozing* may be waken up to carry out rollbacks that are not necessary for maintaining consistency. Second, several nodes in the system are mobile. If all the nodes have to roll back their computations, a large number of messages will be required at the network layer to locate all the mobile nodes. By keeping the number of nodes that need to roll back to a minimum, message traffic (for locating nodes) can be reduced, thus meeting the limited bandwidth restriction imposed by mobile computing.

In some recovery algorithms for static distributed systems only failed nodes are made to roll back their computation [8], [25]. However, [25] requires extensive logging of message contents both at the sender and receiver ends. In [8], the antecedence graph, containing the entire causal relationship, is kept in volatile storage and periodically copied to stable storage. Each computation message has to carry portions of the antecedence graph, significantly increasing the size of the messages. Since *MH*s have a limited memory, extensive logging of information is not feasible. Having the *MSS*s maintain the logs on behalf of the *MH*s will lead to movement of large amounts of data over the static network as an *MH* moves from one *MSS* to another. The bandwidth of the channel between an *MH* and an *MSS* being low, supporting high overhead computation messages of the type described above will be difficult.

We propose a recovery algorithm for mobile computing systems where, instead of all the nodes, only a minimal set of nodes is made to roll back the computation, and extensive logging of messages on stable storage is not required. The concept of dependency is used to minimize the number of nodes that roll back their computations. For example, suppose a node P_i fails and has to roll back. If no new dependency from P_i to P_j has been created since P_j's last checkpoint, there is no need for P_j to roll back in response to P_i's rollback. Only those nodes that have a dependency on the failed node since the latter's last checkpoint need to roll back to maintain global consistency.

5.1 Rollback to a Consistent State

Each node keeps track of all the nodes to which it has sent computation messages using the *send_infect* vector. To recover from a failure, node P_i rolls back to its latest checkpoint and sends rollback requests to all the nodes whose bits are set in its *send_infect* vector. The *send_infect* vector is sent with the rollback requests. When a node P_j receives the first rollback request, it takes the following actions:

1) P_j rolls back to its latest checkpoint.
2) P_j sends a rollback request to every node whose bit is set in P_j's send_infect vector but is 0 in the bit-vector received in the rollback request message. The vector obtained by bit-wise ORing of P_j's send_infect vector and the received bit-vector is sent with each request.

All subsequent rollback requests received by P_j originating due to this failure of P_i are ignored. A data structure similar to trigger (Section 4.1) can be used to indicate the node that initiated the rollback.

The node that initiates a rollback has an initial weight of one. As in Huang's termination detection algorithm [11], a portion of this weight is sent by the initiator with each rollback request. Each time a node propagates the rollback request, it sends a portion of its weight with the corresponding messages. It also sends its residual weight back to the initiator after its rollback is over. The rollback phase terminates when the initiator's weight becomes equal to one. At the end of this phase, the system has been restored to a consistent state. The rollback requests for *MH*s are rerouted to them by the *MSS* to which they were previously connected, through the *MSS* to which they are currently connected. The strategies proposed in [2], [4], [12], [23], [27], [28] can be employed to locate the new *MSS* to which the *MH* is connected.

5.2 Retracing the Lost Computation

Once the system has rolled back to a consistent state, the nodes have to retrace their computation that was undone during the rollback. The following types of messages have to be handled while retracing the lost computation:

- *Orphan messages*: Messages whose reception has been recorded, but the record of their transmission has been lost. This situation arises when the sender node rolls back to a state prior to sending of the messages while the receiver node still has the record of its reception.
- *Lost messages*: Messages whose transmission has been recorded, but the record of their reception has been lost. This happens if the receiver rolls back to a state prior to the reception of the messages, while the sender does not roll back to a state prior to their sending.
- *Out of sequence messages*: This situation arises when the messages do not arrive at the recovering node in the same order as they did originally. For example, let P_i send two messages m_1 and m_2 to P_j. Node P_j rolls back after receiving m_1, and at that time m_2 was in transit from P_i to P_j. When P_j requests P_i to resend the lost messages, m_1 is sent once again. The communication links being FIFO, the second copy of m_1 reaches P_j after m_2.
- *Duplicate messages*: This happens when more than one copy of the same message arrives at a node; perhaps one corresponding to the original computation and one generated during the recovery phase. If the first copy has been processed, all subsequent copies should be discarded. A transparent recovery algorithm should never generate duplicate output messages to the external environment.

The proposed recovery algorithm maintains data structures similar to those in [25]; however, it logs messages in volatile storage only at the sender.

1) Whenever a node sends a computation message, it maintains a copy of it in the volatile storage until the checkpoint at the node (determined by the snapshot collection algorithm) is advanced to a state past the message transmission event.
2) Each node maintains two integer vectors in stable storage: sent[1..n] and received[1..n] where n is the number of nodes. At node P_i, sent[j] and received[j] are equal to the number of computation messages sent to and received from node P_j, respectively, since the beginning of the computation. Both the vectors are initialized to zeroes.
3) Each node logs the order in which messages have been received (not the message itself) from all the other nodes since its last checkpoint, in a queue, QUEUE, maintained in stable storage.

Input messages received by a node from the external environment are logged in stable storage before being processed.

The logs and data structures mentioned above are used for recovery in the following manner: During normal operation, whenever P_i sends a computation message to P_j, it increments sent[j] by one and stamps the outgoing message with the new value of sent[j]. Whenever P_i receives a computation message from P_j, it increments received[j] by one. P_i also adds an entry for P_j to the tail of the QUEUE. When P_i rolls back to its latest checkpoint, it resets received[1..n] to the values corresponding to the state at the checkpoint. The node also sets a pointer to point to an entry of the QUEUE corresponding to the entry immediately following the checkpoint. If no message reception was undone during the rollback, there is no such entry and the pointer is set to null.

1) Having rolled back, when node P_i starts recovery, it broadcasts a RECOVERING(i) message that contains the vector received[1..n].
2) When a node P_j receives the RECOVERING(i) message, it retransmits copies of the messages meant for P_i in its volatile storage whose sent[i] values are greater than the received[j] value in the broadcast message.
3) After broadcasting the RECOVERING(i) message, the incoming messages, m, from the other nodes, P_j for all $j \in \{1, \ldots, n\}$, are received and processed in the following manner:
   a) If sent[i] in the message is equal to received[j] + 1 at P_i and the pointer is non-null and pointing to P_i in the QUEUE, then the message can be immediately processed. The pointer is moved to the next entry in the QUEUE.

b) If the sent[i] value in the message is less than or equal to received[j], then it is a duplicate message and is ignored.
c) Otherwise, the message has been received out of sequence—there are messages from other nodes to P_i that have to be processed first. So, m is buffered and not processed until the condition specified in 3a is satisfied.

Orphan messages cannot arise during rollback and recovery because whenever P_i rolls back after sending a message to P_j, it also sends a rollback request to P_j since send_infect[j] has been set to 1. Hence, P_j rolls back erasing the record of the reception of the message. The problem of *lost messages* is solved by logging messages in volatile storage at the sender. These messages can be retransmitted during recovery on receiving the RECOVERING message. *Out of sequence* messages and *duplicate* messages are handled as mentioned above in 3b and 3c, respectively. In order to prevent duplicate output messages from being sent, an output message is not sent to the external environment until the checkpoint is advanced to a state past the generation of the output message.

6 Comparison with Earlier Work

In the Chandy-Lamport algorithm [7], which is one of the earliest snapshot collection algorithms for a system with static nodes, system messages are sent along all the links in the network during snapshot collection. This leads to a message complexity of $O(n^2)$. In the proposed snapshot collection algorithm, system messages need not be sent along all the links in the network. The number of system messages required is proportional to the number of channels in the interconnection network along which computation messages have been sent since the last snapshot collection. Therefore, the average message complexity of the proposed algorithm is lower than Chandy-Lamport's algorithm.

Acharya et al. [1] were the first to present an asynchronous snapshot collection algorithm for distributed applications on mobile computing systems. They give two reasons why they consider synchronous checkpointing to be unsuitable for mobile systems:

1) high cost of locating *MH*s because in the Chandy-Lamport kind of algorithm, an *MH* has to receive REQUESTs along every incoming link and
2) nonavailability of the local snapshot of a disconnected *MH* during synchronous checkpointing.

The synchronous algorithm proposed in this paper overcomes both these shortcomings; by conveying the transitive closure of dependency information through R_i, the number of REQUESTs is reduced, thus reducing the cost of locating the *MH*s. Also, the local snapshot of a disconnected mobile host MH_i is always available, as $disconnect\_snapshot_i$, at the *MSS* to which it was last connected.

In [1], an *MH* has to take its snapshot whenever a message reception is preceded by a message transmission at that node. This may lead to as many local snapshots being taken as the number of computation messages (if the transmission and reception of messages are interleaved). This is likely to impose a high checkpointing cost on the nodes. Considering that message communication is much more frequent than initiations of synchronous snapshot collection, or movement of *MH*s from one *MSS* to another, the proposed algorithm will require the nodes to take their local snapshots much less frequently than the algorithm in [1]. The lazy checkpoint advancement in the proposed algorithm overcomes yet another potential drawback of synchronous checkpointing. During the lazy phase, messages needed for checkpoint advancement are spread over a period of time rather than being bursty during a short duration. Such low density traffic is suitable for the low bandwidth communication networks of the mobile computing systems.

In Venkatesan's algorithm [24], a node sends out *markers* (corresponding to REQUESTs in the proposed algorithm) on all the outgoing edges along which computation messages have been sent since the last checkpoint. However, as already explained in Section 3, in order to efficiently collect a consistent snapshot, checkpointing REQUESTs need only be propagated from the receiver of messages to the sender, not the other way round as in [24]. Therefore, the proposed algorithm, because it propagates checkpointing decision in the receiver to sender direction, makes a minimal set of nodes to take its snapshot and is more suited for mobile computing systems than the algorithm given in [24].

The main advantage of our algorithm over the synchronous Koo-Toueg algorithm [13] is that the underlying computation is never suspended during snapshot collection in our algorithm. This significantly reduces the run-time overheads of the algorithm. Moreover, in the snapshot collection algorithm of Koo-Toueg, only direct dependencies are maintained, as opposed to transitive dependencies maintained by our algorithm. Snapshot requests propagate faster along the transitive dependency chain as compared to the direct dependency chains. Knowledge about transitive dependencies also reduces the number of snapshot REQUEST messages required by the algorithm. In [13], a node P_i sends snapshot requests to all the nodes P_j on which it is *directly* dependent. In our algorithm, if P_i knows that a REQUEST has already been sent to P_j by some other node, then it does not send a REQUEST to P_j. This information is carried by the bit-vector in REQUEST messages. If multiple snapshot collections are initiated concurrently in [13], they may all have to be aborted. In [19], we present a strategy to handle multiple independent and concurrent initiations of snapshot collection.

In an uncoordinated checkpointing, as described in [5], [22], every node may accumulate multiple local checkpoints and logs in stable storage during normal operation. A checkpoint can be discarded if it is determined that it will no longer be needed for recovery. For this purpose, nodes have to periodically broadcast the status of their logs in stable storage. The number of local checkpoints depends on the frequency with which such checkpoints are taken, and is an algorithm tuning parameter. An uncoordinated checkpointing approach is not suitable for mobile computing for a number of reasons. If the frequency of local checkpointing is high, each node (including *MH*s) will have multiple local checkpoints requiring a large memory for stor-

age. The limited memory available at the *MH*s is not conducive for storing a large number of checkpoints. When an *MH* disconnects from an *MSS*, all its local checkpoints have to be stored at the *MSS*. When the *MH* reconnects to a new *MSS*, all these checkpoints have to be transferred from the old *MSS* to the new *MSS*, incurring high communication overheads. The memory and communication overheads can be reduced by taking the local checkpoints less frequently. However, this will increase the recovery time as greater rollback and replay will be needed. In the coordinated checkpointing algorithm presented in this paper, most of the time each node needs to store *only one* local checkpoint—permanent checkpoint, and *at most* two local checkpoints—a permanent and a tentative checkpoint only for the duration of snapshot collection.

In Venkatesan and Juang's optimistic failure recovery algorithm [26], no dependency information is sent with the computation messages. However, several iterations may be needed for all the nodes to roll back to mutually consistent states at the time of recovery. This is a high price to pay considering that the low overheads associated with the computation message of our algorithm help accomplish consistent rollback in one iteration. Moreover, the mobile nodes may change their location between iterations, complicating the rollback process.

The recovery algorithms proposed in [8], [25] ensure that only the failed nodes are rolled back. However, they require extensive logging of messages and high communication overheads. The algorithm proposed in this paper has lower storage and communication overheads than [8], [25] and may require few operational nodes to roll back. Our algorithm has slightly higher communication overheads than Venkatesan's algorithm [24], but much smaller delays. Thus our algorithm has slightly higher overheads than the most economical recovery algorithm for static networks, and a slightly greater delay than the fastest recovery algorithm for static networks. However, it does not suffer from the drawbacks, i.e., extensive logging and high communication overheads, of either. So, it is ideal for mobile computing systems where storage and communication bandwidth are at a premium and time constraints are not very rigid.

Manetho [8] and the recovery scheme described in [5] have low overheads for failure-free operation. However, the recovery procedure is complicated. This may be acceptable for a static network where communication is more reliable and the constituent nodes are robust, with rare incidences of failure. Also, the execution time for rollback and recovery in [5] increases significantly with increases in the number of nodes in the system and the number of checkpoints maintained by each node in the system. Hence, scalability is sacrificed for a low overhead failure-free operation.

Mobile computing systems are not as robust as the static systems. A mobile host can fail due to a variety of reasons. It may be exposed to adverse weather conditions, its power source may get depleted in the middle of an important operation, or it may be affected by heavy impact, vibrations, etc. Sometimes, the availability of only low bandwidth communication links between an *MH* and its *MSS* may lead the underlying network protocol to incorrectly conclude that either the *MH* or the *MSS* has failed, thus triggering the recovery algorithm. Hence, the recovery algorithm will be invoked more frequently in mobile computing systems than in static systems. For such systems, the simple recovery scheme proposed in this paper is more suitable than the complicated recovery scheme of [5], [8]. Moreover, the increasing popularity of mobile computing will lead to an ever increasing number of mobile nodes participating in executing bigger and bigger distributed applications. As the recovery time in [5] increases with increasing number of nodes, it is not suitable for mobile computing systems. Thus, the proposed recovery scheme for mobile systems is scalable due to its simplicity and low overheads.

7 Conclusions

A mobile computing system consists of mobile and stationary nodes, connected to each other by a communication network. The demand for such systems is exploding due to the proliferation of portable computers and advances in communication technology. An efficient recovery mechanism for mobile computing systems is required to maintain continuity of computation in the event of node failures. In this paper, we developed low-overhead snapshot collection and recovery algorithms for distributed applications in a mobile computing system that meet the requirements of node mobility, energy conservation, and low communication bandwidth.

Dependency information among nodes is used to incrementally advance the global snapshot of the system in a coordinated manner and to determine the minimal number of nodes that need to roll back in response to node failures. The proposed snapshot collection algorithm is nonintrusive—it does not require the participating nodes to suspend their computation during snapshot collection. The lazy advancement of the checkpoint, after coordinated snapshot collection has terminated, leads to the checkpointing overheads being amortized over a period of time. As the underlying computation is never suspended during snapshot collection, the run-time overheads are low. Each system message has a small size, and incurs a low overhead as the information about dependencies can be conveyed using just a bit-vector. This compares favorably with existing implementations like Manetho [8] where the antecedence graph, incorporating information about the exact ordering of message transmissions and receptions at the nodes, is piggybacked on each message.

We used dependency information to develop a minimal recovery algorithm. Consequently, the computation that is lost due to rollbacks is less than that in a number of algorithms proposed for static distributed systems. The recovery algorithm has low storage and communication overheads. The time to recover from node failures and to restore the system to a consistent state is less than that needed by some of the most economical (low overheads) recovery algorithms. Our recovery algorithm is a compromise between two diverse recovery strategies—fast recovery with high communication and storage overheads and slow recovery with very little communication overheads. Hence, the algorithm is suitable for mobile computing systems.

In summary, we have provided efficient techniques that are suitable for snapshot collection and recovery in mobile computing systems.

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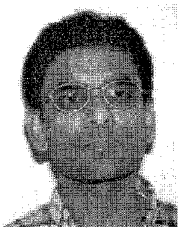

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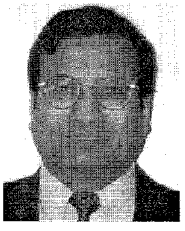

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