Ordering in Mobile Networks Using Integrated Sequencers *

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Abstract. Distributed applications mostly interact by exchanging messages. For this purpose the messages often need to be ordered. Since today more and more mobile devices are used message ordering in mobile networks is increasingly important. Most ordering protocols for mobile networks use vector clocks or matrices. In static networks often multicast trees ensure message ordering. In this paper we propose a multicast protocol which ensures total order in a mobile environment. It uses sequencers organized in a tree-structure to obtain this total order, and introduces no extra-cost. This is because sequencers form no additional part of the network, in fact they are integrated and embedded network components.

1 Introduction

Message ordering is needed in nearly all distributed applications, such as object replication, CSCW systems, or distributed monitoring. With advanced use of mobile devices such applications are more and more expanded to mobile environments. For wired networks several multicast delivery algorithms are based on trees, such as CBT [**?**] and PIM [**?**]. In fact they are only used for delivering multicasts and not for ordering. Also they do not contain elements for handling mobility (e.g. handling handoffs). Without such techniques dynamic networks are impossible, so algorithms are restricted to static communication infrastructures. However multicast trees are an excellent structure to be used for message delivery and they can be combined with ideas of sequencers. In the following we present an ordering approach based on multicast trees and sequencers for both message delivery and ordering usable in mobile environments.

The paper is organized as follows: Section 2 introduces the general system and the proposed model. The algorithm is presented in Sect. 3. In subsections of Sect. 3 we specify algorithms for causal and total order, dynamic groups and handoffs, and we sketch a correctness proof. Section 4 pictures results of a performance evaluation. Related work is shown in Sect. 5. Conclusions and future work can be found in Section 6.

2 Concepts and System Model

The mobile network we assume is represented by 2 kinds of nodes: *mobile hosts* (MH) denoted as h_x and *mobile support stations* (MSS) denoted as S_x. Mobile hosts h_x are

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connected by a wireless link to exactly one MSS, which is called *local MSS* denoted as $S(h_x)$. We assume connections as reliable and FIFO. Messages from h_x to h_y can only be delivered via their local MSSs. The set of all MHs is denoted as $\mathcal{H} = \{h_1, h_2, ...\}$. MHs with the MSS S_x as local MSS are denoted as $\mathcal{H}(S_x) = \{h_x \in \mathcal{H} | S(h_x) = S_x\}$.

MSSs are connected by an arbitrary wired network. Out of it we built a connected acyclic undirected graph $\mathcal{G} = (\mathcal{S}, \mathcal{E})$ as an overlay network in the application layer. $\mathcal{S} = \{S_1, S_2, ...\}$ means the set of all MSSs, $\mathcal{E}$ is the set of edges (connections). The neighbors of S_x are called $\mathcal{N}(S_x) = \{S_y \in \mathcal{S} | (S_x, S_y) \in \mathcal{E}\}$. The property of an acyclic graph is no restriction and introduces no problems concerning the network partition in case of any link errors: A path between each pair of nodes is found as long as any connection in physical links exists. Typically, the wired network has a high bandwidth and a low propagation delay. Connections are also assumed as reliable and FIFO.

Online MHs $h_x \in \mathcal{H}$ are members of several multicast groups (MG) $\mathcal{G}(h_x)$. For all $g_x \in \mathcal{G}(h_x)$ MH h_x receives all messages sent to g_x and vice versa it can send messages to g_x. This assumption is called closed groups in literature [**?**]. The set of MGs all $h_x \in \mathcal{H}(S_x)$ are members of is denoted by $\mathcal{G}(S_x) = \bigcup_{h_x \in \mathcal{H}(S_x)} \mathcal{G}(h_x)$. The set of MGs the MHs of MSSs $M \subseteq \mathcal{S}$ are members of is defined by $\mathcal{G}(M) = \bigcup_{S_x \in M} \mathcal{G}(S_x)$.

As defined by Lamport's *happend before* relation [**?**] (denoted by $\rightarrow$) message m_x causally precedes all messages m_y for which holds $m_x \rightarrow m_y$. Multiple group causal ordering (which is considered in this paper) is obtained if the former applies to messages across groups. So if $m_x \in g_x \wedge m_y \in g_y \wedge g_x \neq g_y \wedge m_x \rightarrow m_y$ then for all MHs which are members of both groups, m_x is delivered before m_y. Single group total ordering means that messages of each MG g_x are delivered in the same order to all members of g_x. That definition of total order is regarded in this paper.

3 Algorithm

Our algorithm uses a sequencer-based approach to obtain total order. Unlike other proposals [**?**,**?**,**?**] our sequencers do not cause extra-costs in delivering multicasts. So the sequencers are no additional parts of the network, in fact they are integrated and embedded components. Our algorithm works as follows: To send a multicast h_x sends a multicast message to $S(h_x)$. Then $S(h_x)$ delivers this message to all other MSSs which again deliver the message to their MHs (including the sender). All $S_x \in \mathcal{S}$ know the participants of all MGs among $\mathcal{H}(S_x)$. Also MSSs exchange information about MHs with other MSSs by exchanging $\mathcal{G}(S_x)$ and $\mathcal{G}(\mathcal{N}(S_x))$ with all neighbors $\mathcal{N}(S_x)$. According to that information MSSs deliver multicast messages to neighbors and MHs. This is shown in Fig. 1. 6 MSSs and 4 MHs are illustrated. MH h_1 is e.g. member of MGs g_1 and g_3. S_3 forwards multicasts of group g_1 to S_1 and S_4, multicasts of groups g_2 and g_3 to S_1 and multicasts of g_4 to S_4. This information about forwarding is updated by MSSs in case of changes. So each MSS can forward multicasts of g_x to all MHs of g_x and to all MSSs with respective MHs in their subtrees. Therefore only information about connected MHs and neighbor MSSs is required.

Causal Order. Causal order is a side effect from the tree-based overlay network structure used and the assumption of FIFO message exchange between links. We can ob-

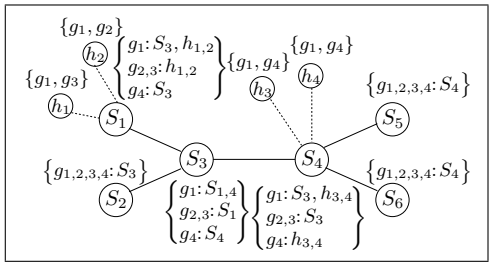


Fig. 1. Overview of topology, group memberships, and forwarding information

tain causal order with the characteristic that messages in MSSs are handled in order of their arrival. The informal explanation for ensuring causal order is that if message m_x causally precedes message m_y in any MH $h_x \in \mathcal{H}$ then m_x is delivered to each MH before m_y. That is due to handling messages in order of their arrival, the assumption of FIFO and the fact that there is a unique path in overlay network for messages of 1 MH to all other MHs. That also holds for messages of different groups in all MHs that are members of both of these groups. A more detailed correctness proof can be found later.

Total Order. To obtain total order with respect to each group we use a sequencer for each group. The sequencer is any MSS in the network. Each MSS knows in which directions the sequencers can be found for all MGs. That knowledge of sequencers is achieved by exchanging messages with neighbors. To multicast a message m_x MH h_x sends m_x to its local MSS $S(h_x)$ that is sending the multicast in direction of MSS S_x acting as sequencer. When the message is delivered to sequencer S_x by MSS S_y the order of arrival of multicasts at S_x is the total order for that group g_x. Then S_x sends the multicast to all neighbors except the source $\mathcal{N}(S_x) \setminus \{S_y\}$ with a label that the multicast is ordered now. So it can be directly delivered by MSSs in that subtree to their MHs of group g_x. S_x also sends this multicast in direction of its source S_y. There and in the whole subtree that multicast is also delivered to all members of MG g_x.

Moving the Sequencer. To minimize the extra cost of multicast delivery a sequencer has to be located in a central network position with respect to the MHs participating in its MGs. At startup an arbitrary S_x is used as sequencer for group g_x. When multicasts are sent S_x counts the number of multicasts which have arrived from each neighbor and connected MHs. If from a neighbor S_z more multicasts for group g_x arrive than from the sum of the multicasts of group g_x of the connected MHs and all other neighbors $\mathcal{N}(S_x) \setminus \{S_z\}$ then the sequencer should move into direction of S_z in the overlay network. To prevent frequent location changes we can multiply the former sum with a factor greater than 1.0. Additionally, we allow location changes only after a certain amount of time. That movement of the sequencer from S_x to S_z happens as an atomic operation to other nodes (MHs and $\mathcal{S} \setminus \{S_x, S_z\}$). It can be easily realized with that procedure: S_x sends $takeOver(g_x)$ to S_z. When $takeOver(g_x)$ arrives at S_z it replies $takenOver(g_x)$ and

waits for an $ok(g_x)$ from S_x. Now only messages from S_x are handled by S_z (and never send back to S_x because S_x is still the sequencer), messages from other neighbor MSSs are queued. When $takenOver(g_x)$ arrives at S_x it replies $ok(g_x)$. Then S_x works as normal MSS. When $ok(g_x)$ arrives at S_z it acts as sequencer and handles all messages, including queued ones. This ensures that the movement of sequencers is transparent to other nodes. Other metrics and heuristics for placing sequencers can be found in [**?**].

To join the causal and the total order approach we have to introduce the following concept: A multicast m_y of group g_y from MH h_x can only be sent in direction of the sequencer after any multicast m_x of g_x from h_x with $m_x \rightarrow m_y \wedge g_x \neq g_y$ has already been delivered to h_x. That can be implemented in local MSSs transparent to MHs.

Dynamic Groups. If a MH changes its MGs or goes offline/online MSSs update their information $\mathcal{G}(S_x)$ and $\mathcal{G}(\mathcal{N}(S_x))$. If no MH connected to S_x is member of a group g_x anymore ($g_x \notin \mathcal{G}(S_x)$) and messages of g_x have at most be forwarded to neighbor S_y in direction of sequencer of g_x then neighbors $\mathcal{N}(S_x)$ do not send messages related to that group in future (sets $\mathcal{G}(S_x)$ are updated in $\mathcal{N}(S_x)$) to S_x. If a MSS S_x is newly interested in a group (that means $g_x \notin \mathcal{G}(S_x) \wedge g_x \notin \mathcal{G}(\mathcal{N}(S_x) \setminus \{S_y\})$) S_x is sending a $ping(g_x)$ message in the direction of the current sequencer. That message is delivered as ordinary multicast messages. When a MSS interested in g_x is met or the sequencer is reached a $pong(g_x)$ message is replied to the sender. When that $pong(g_x)$ arrives at S_x it can inform the source MH that from now on all multicast messages are delivered (all MSSs on the way to the sequencer realized the group membership because of the unique path to the sequencer and the frequent update of information regarding MGs).

Handling Handoffs. To handle handoffs, ensure correct delivery order and cause no message losses we have to introduce the following handoff procedure: Consider that h_x moves from S_x to S_y. First h_x registers all MGs $\mathcal{G}(h_x)$ at S_y. So S_y sends $ping$ messages to all sequencers of groups $\{g_x \in \mathcal{G}(h_x) | g_x \notin \mathcal{G}(S_y)\}$ and receives respective $pong$ messages. If all $pong$ messages have arrived (or $\mathcal{G}(h_x) \subseteq \mathcal{G}(S_y)$) S_y still does not deliver messages of those groups to h_x, instead it only stores them. Furthermore an $adopt(h_x)$ message is sent to S_x. When $adopt(h_x)$ is delivered to S_x it stops forwarding multicasts to h_x and sends a $relased(h_x)$ message to the new local MSS S_y. That message also contains the identifications from last sent messages of all groups $g_x \in \mathcal{G}(h_x)$. Then S_x acts as in the case if h_x leaves all groups $\mathcal{G}(h_x)$. When $relased(h_x)$ arrives at S_y it discards all stored messages of corresponding groups less or equal then the received identifications and delivers the remaining messages in order of receiving.

Correctness Proof. Now we prove the correctness of our algorithm. In the following we will show that the algorithm delivers in causal order between groups and in total order within single groups. Each message is delivered exactly once (safety) and after a finite amount of time (liveness). We only show sketch-proofs because of limited space.

Proof (safety property, causal order). Suppose messages m_x and m_y, such that $m_x \rightarrow m_y$ holds and $m_x \in g_x \wedge m_y \in g_y$. Let m_y be sent by h_y. If $m_x \rightarrow m_y$ then h_y has received m_x before sending m_y. So causal delivery in h_y is proven. Suppose that m_y is

delivered first in any h_x. So there is a shorter path from $S(h_y)$ to h_x than m_x has taken. That is a contradiction to the tree-structure and FIFO message exchange. □

Proof (safety property, total order). Suppose messages $m_x \in g_x$ and $m_y \in g_x$ and m_x is delivered before m_y in any MH h_x. Suppose m_y is delivered before m_x in any MH $h_y \in \mathcal{H} \setminus \{h_x\}$. That means there is a shorter path from the sequencer to h_y in case of delivering m_y then in case of delivering m_x. So we have a contradiction to the tree-structure used and the FIFO message exchange. □

Proof (liveness property). Links between all network nodes support reliable message exchange. There is only a bounded number of messages to be handled at each MSS (unmarked multicast messages are spread away from sender and the unique sequencer spreads these messages further away and back to sender). Thus, assuming each handling takes a bounded time, each message is delivered after a finite amount of time. □

4 Performance Evaluation

We have evaluated the performance of the main algorithm (total order using the described approach) using a simulation on OMNeT++ [**?**]. The used network parameters are shown in Table 1. We want to evaluate the performance of the network of MSSs, so propagation delay and bandwidth of wireless links are neglected. We also use only one MG. Our results describe the hypothetical maximum number of processable multicasts. Using a real mobile network protocol, such as GPRS [**?**], there are technical limits: Assuming 56 kbit/s downstream and a message size of 100 byte the maximum number of multicasts per second without buffering is approx. 560. But with our hypothetical number we obtain information about the behavior of the connecting network. We also recognize limitations and can derive the behavior in complex cases, such as more MGs.

In the experiments we evaluate the influence of several parameters on the average network traffic per multicast and processing time per multicast (time per multicast = reciprocal value of the average number of processable multicasts). Here we plot time per multicast. We assume an equal distribution of multicasts between MHs. Also an equal distribution of MHs to MSSs and a symmetric network topology is assumed, which is shown in Fig. 2 with the density parameter $\sigma = 3$ (number of subordinate MSSs) and 4 levels of MSSs. In the following subsections we describe the evaluation of the influence of the number of MSSs, number of MHs, and the location of sequencers.

Number of MSS. When the number of MSSs is increased the average time to deliver a multicast should decrease significantly. The network traffic per multicast should differ only to a small extend because the main load is produced by the delivery of multicasts to MHs. The influence on time and network load per multicast is shown in Fig. 3(a), (b). In the experiments we choose 3 different settings. The sequencer is the central network node, the density parameter is chosen with $\sigma = 3$. We vary the number of MSSs from 1 to 150. As expected the time per multicast decreases significantly (logarithmic scale in Fig. 3(a)) if the number of MSSs grows. Using 150 MSSs the delivery time is approx. 67 to 136 times faster than using 1 MSS. Adding more MSSs means only a very low increment of network traffic. The graph shows almost constant network load, because delivery to the MHs is really more crucial than communication among the MSSs.

Table 1. Overview of network parameter dimensions used

Parameter	Chosen setting
number of MSSs/MHs	1 to 1,023/1,000 to 20,000
data rate/propagation delay wired links	100 mbit/s / 0.5 ms
computation delay en-/decapsulate/serve a message	0.1 / 0.1 / 0.2 ms
size of multicast message (user data)	100 byte

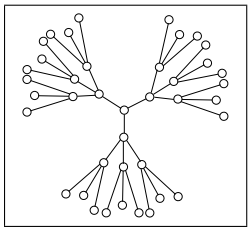
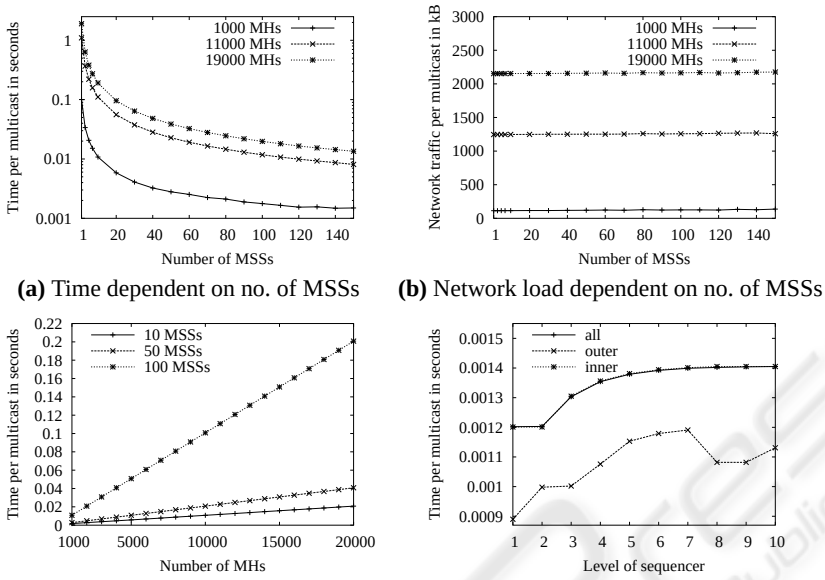


Fig. 2. Symmetric network used in experiments with $\sigma = 3$ and 4 levels of MSS

Number of MH. With a growing number of MHs the network traffic and the time per multicast should increase. That is shown in Fig. 3(c) using different numbers of MSSs. A density parameter $\sigma = 3$ is used in this experiment. We evaluate 1,000 to 20,000 MHs. Here we only plot the average time per multicast. The network traffic is a straight line from approx. 120 kB to 2,3 MB. The time per multicast linearly increases with a growing number of MHs. That is because each MH introduces a constant amount of extra work for MSSs. Using 10 MSSs the time per multicast is approx. 12 times higher when using 20 times more MHs, in case of 100 MSSs the time is 19 times higher.

Location of Sequencer. A main assumption for our algorithm is that a movement of sequencers influence the average time per multicast. If a sequencer is in a central position according to the MHs of its group the time per multicast should be smallest. In our experiments we choose a setting with 1,023 MSSs and $\sigma = 2$. So we have a symmetric network with 10 levels of MSSs. 5 MHs per MSS have been connected in experiments. We evaluate the time per multicast in 3 cases: (all) - MHs are connected to all MSSs, (outer) - MHs on outer level, (inner) - MHs on 7 inner levels. Figure 3(d) shows the average time per multicast. The best performance is achieved in case (outer). There approx. 4 times as much MHs are members of the same MG as in case (inner), but the time per multicast is much lower. The reason is that inner MSSs are not involved in delivering multicasts to MHs but only to MSSs. In case (inner) we can see opposite results: Even if there are 8 times less MHs as in case (all) approx. the same number of multicasts is delivered (inner MSSs always have same high load). In all 3 cases we can observe that a central position of the sequencer means lower times per multicast. In our experiments the increase of performance goes up to 21%. The traffic is not shown: We have nearly constant load with the highest in case (all), followed by (outer) and (inner).



(a) Time dependent on no. of MSSs **(b)** Network load dependent on no. of MSSs

(c) Time dependent on no. of MHs **(d)** Time dependent location of sequencer

Fig. 3. Influence on algorithm dependent on no. of MSSs/no. of MHs/location of sequencer

5 Related Work

There are some multicast protocols using a tree-approach: Core Based Trees (CBT) [**?**], the Protocol Independent Multicast (PIM) [**?**] and also the Border Gateway Multicast Protocol (BGMP) [**?**] can be found. All these protocols construct propagation trees for MGs. Messages are sent towards the root. The roots do not adapt to network changes. But these protocols are only involved in propagating a multicast and not in ordering. For sequencer ordering there exist mainly 3 approaches: The first is to ask the sequencer for a sequence number and send a message with that number (e.g. implemented by Armstrong et al. [**?**]). Another idea is to multicast to group members and the sequencer. Then sequencers also send messages determining the order (e.g. realized by Birman et al. [**?**]). And the last is to send a multicast to the sequencer, which forwards to all group members (e.g. done by Navaratnam [**?**]). That idea is also considered in our approach with the improvement that sequencers are embedded parts of the delivery tree and there is no overhead in both delivery time and network traffic. Nevertheless mobility is not considered in those protocols [**?**,**?**,**?**]. Order protocols dealing with mobility use vector clocks or matrices, such as [**?**,**?**]. Or they use coordinators [**?**] normally not involved in communication to obtain order, indeed they are a system's bottleneck.

6 Conclusions & Future Work

We have presented a new approach for a sequencer-based ordering of multicasts in mobile networks. We obtain total order of the multicasts in one multicast group and causal order for messages across groups. Our approach chooses an arbitrary MSS as sequencer in the beginning. Then, according to the behavior of MHs the sequencer moves within the network to minimize the distance to MHs of its group. The sequencer is placed in a propagation tree of multicast messages so there is no extra cost for ordering messages via a sequencer. In fact sequencers are integrated and embedded network components which forward messages in any case. We have also proposed algorithms for dynamic group changes and a handoff procedure for changing local MSSs.

We have simulated the performance of our approach by evaluating influences of different parameters. With this simulation we have shown that a sequencer should be located in a central position within the network according to MHs participating in its group. So we can increase processable multicasts and decrease network traffic. We have also shown the influence of the quantity of MSSs and MHs. In future we want to evaluate the performance of the proposed handoff procedure and the overhead of the sequencer movement itself.