A scalable causal broadcast that tolerates dynamics of mobile networks

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ABSTRACT

Causal broadcast is at the core of collaborative applications, distributed databases, conferencing, or social networks. Existing causal broadcast algorithms are either not scalable or cannot be implemented on mobile networks because they do not take into account the features of these networks: limited capacities of nodes (computation, storage, energy), unreliable communication channels, and the dynamics of connections due to node mobility, node failure, and join/leave of nodes. This work presents a causal broadcast algorithm for mobile networks. The algorithm is scalable: control information piggybacked on messages and maintained on nodes is of small size. Experiments conducted on OMNeT++, a realistic network simulator, confirms the effectiveness of our causal broadcast protocol, rendering causal broadcast affordable in mobile networks.

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1 INTRODUCTION

Causal broadcast is a fundamental group communication service largely used by many applications such as distributed databases, publish/subscribe systems, collaborative applications, or distributed social networks. It ensures that messages are delivered to all nodes exactly once, preserving causal relation between messages, i.e., the delivery of a message respects Lamport's happened-before relationship [11]: if the broadcast of a message m precedes the broadcast of a message m′, then no process delivers m′ before m.

Due to scalability issues, changes in network topology, and node resource limitations [10], the implementation of a causal broadcast service for mobile networks composed of mobile hosts and static support stations is a challenge. In such networks, stations are connected through a wired network, while a station communicates through the wireless network with hosts inside its geographic coverage area, denoted cell. Hosts move between cells and only communicate with the station of their current cell. They have memory, computational power, and battery life limitations [10][6][17][2] and are subject to transient or permanent failures when, for instance, its battery becomes flat, or a hardware failure occurs. Interferences cause message losses on the wireless network. To the best of our knowledge, no causal broadcast solution handling those characteristics has been proposed.

Existing implementations of causal broadcast either piggyback information on messages [14][17][8][13] or organize nodes in logical topologies in which messages are disseminated through reliable FIFO channels [9][16]. The first approach is not suitable for mobile networks that contain many mobile hosts, due to scalability issues, because the size of information piggybacked on messages either grows with the number of nodes [8][13], or with the message load [14][17]. The second approach [9] [16] ensures that messages are implicitly causally ordered at reception. Therefore, no information is piggybacked on messages, making that approach scalable. However, [9] considers a static network, and the dynamic model of [16] is not applicable to mobile networks. Moreover, [9][16] require reliable FIFO channels, which are not provided by mobile networks, even with TCP, because a host moving to a new cell drops the connection with its previous cell, and pending messages of that connection are lost.

Several works address causal multicast in mobile networks [6] [17][2][3][12]. However, they usually make unrealistic assumptions such as reliable [6][17] and/or FIFO [3][12] channels, or reliable host connection protocols. In addition, they do not address the problem that hosts might fail to connect to a cell's station before moving to another cell, which might lead to many concurrent connection initializations. Furthermore, they usually consider that hosts are reliable, i.e., they never fail, and the proposed solutions do not scale. Finally, causal multicast requires additional information to handle multicast groups, not necessary for causal broadcast.

Stations handle interferences on the wireless network by caching messages for retransmission. Discarding cached messages once they become obsolete is an important issue to deal with. Some existing implementations, such as [6][3], propose costly centralized solutions since the source station that initially broadcast a message coordinates the protocol for discarding it from all other stations, inducing a high overhead of message traffic (acknowledge messages) and memory storage (a message is cached at all stations even if only one station requires it).

This work presents a scalable causal broadcast algorithm designed for mobile networks. Hosts can join/leave the network and fail, permanently or transiently, at any time. They move freely and might be temporarily disconnected from the network when out of range of all stations. We assume no reliable connection protocol, and the algorithm handles multiple concurrent connections by the same host. Resource limitations of hosts are handled by keeping causal information at stations, while hosts only keep very little control information. Messages piggyback only a few integers as control information. Contrarily to existing centralized solutions [6]

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[3], the discarding of obsolete messages cached at stations is decentralized: a station discards a message once all hosts connected to it acknowledged the message. Consequently, stations only cache necessary messages, and no extra messages are exchanged for message discarding.

Summing up, the proposed causal broadcast algorithm is scalable in both the number of hosts and stations, has a low message traffic and storage overhead, while handling mobile network dynamics without the constraining assumptions of FIFO wireless links [9][16][15] or causal multicast approaches [6][3].

Experiments were conducted over OMNeT++/INET [21]. The proposed algorithm is compared to [6], a causal multicast algorithm for mobile networks which we extended to causal broadcast. Experiments confirm that our algorithm outperforms the latter.

The paper is organized as follows. Section 6 discusses related work. Section 2 presents the background and Section 3 the model. Section 4 describes the proposed causal broadcast algorithm. Section 5 presents the experimental results. Section 7 concludes the paper.

2 BACKGROUND

Causal order ensures that nodes deliver messages while respecting the causal relation between them, as defined by the happened-before relation [11] introduced by Leslie Lamport:

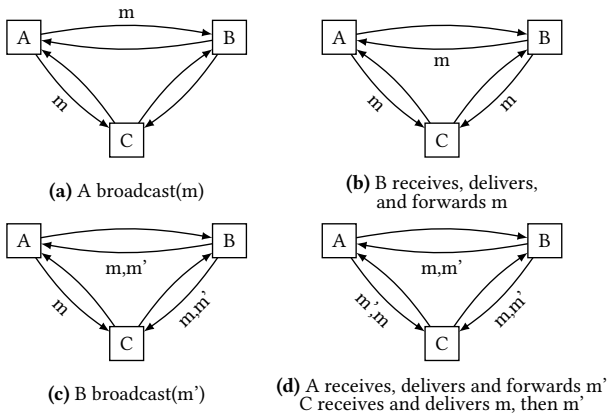
Happened-before relation: *Considering two events* e_1 *and* e_2, e_1 *causally precedes* e_2, *or* $e_1 \rightarrow e_2$ *iff: (a)* e_1 *and* e_2 *occur on the same process and* e_1 *precedes* e_2 *or (b) for a message* m e_1*=send(m) and* e_2*=deliver(m) or (c) there exists an event* e_3 *such that* $e_1 \rightarrow e_3$ *and* $e_3 \rightarrow e_2$.

Causal broadcast is a group communication service that provides the application processes with two primitives *co-broadcast(m)*, that broadcasts a message m to all nodes, and *co-deliver(m)*, that delivers m to the application. Causal broadcast is defined by the following properties [15]:

Causal broadcast: *Validity.* If a process co-delivers a message m from a process q, q previously co-broadcasts m.
Integrity. A process co-delivers a message m at most once.
Causal order. The delivery order of messages follows the happened-before relationship: *co-broadcast(m)* $\rightarrow$ *co-broadcast(m')* $\Rightarrow \nexists$ process q | *co-deliver(m')* $\rightarrow$ *co-deliver(m)*.
Termination. A message co-broadcasted by a correct process is co-delivered by all correct processes.

The delivery of a message is delayed until all messages that causally precede it are delivered. Usually, in mobile networks, stations discard messages once all hosts delivered them. Hosts that join the network will, therefore, not receive and deliver these messages.

Our algorithm extends the FIFO dissemination approach proposed in [9] to mobile networks. The algorithm of [9] ensures causal order through FIFO dissemination in static networks where reliable nodes are connected by reliable FIFO channels, thereby ensuring that no path exists over which messages travel out of causal order. For example, in Figure 1 *A* broadcasts m, which causally precedes



(a) A broadcast(m)
(b) B receives, delivers, and forwards m
(c) B broadcast(m')
(d) A receives, delivers and forwards m'
C receives and delivers m, then m'

Figure 1: Causal broadcast by dissemination [9]

m' broadcast by *B*. All nodes receive m before *m'* since all nodes forward m at reception on all their channels.

3 MODEL

Mobile networks are composed by mobile hosts, denoted *host*(s), and static support stations, denoted *station*(s). Hosts and stations communicate through message passing. Applications running on hosts use a group communication service to join and leave the network, as well as to broadcast messages to all hosts and deliver them in causal order.
The characteristics of *stations* are the following:

- Each station is at the center of a cell, corresponding to the area covered by its antenna's transmission range.
- Stations are supposed reliable and do not move or leave the network, because a failing station would disconnect the area covered by it, and cell overlapping should be avoided (even though it cannot be realistically completely prevented) because of interferences on the wireless network. Hence, we assume hardware replication for stations.
- Stations do not have energy limitations and have much more storage and computational capacity than hosts.

The characteristics of *hosts* are the following:

- A host is connected to at most one station (generally the closest one) at any given moment, and communicates with the system through that station, by sending messages on the wireless network.
- A host can join and leave the network at any moment. A host that joins the network will not deliver those messages that the station to which it connects has previously discarded.
- Hosts move freely inside and outside cells.
- Hosts might temporarily or permanently fail. For example, a host is temporarily faulty until its battery is recharged, or is permanently faulty if it has a hardware failure. A faulty host stops sending, receiving, and processing messages, and loses all variables stored in volatile memory.
- Hosts have computational, storage, and energy limitations.

The wireless network is unreliable, due to interferences that lead to message losses while stations are connected by a high-speed

wired network, which is FIFO and reliable, and over which is built a static logical tree-based overlay.

Hosts can be in the states *up* or *down*. A station controls the state of hosts connected to it: it considers a connected host as down if the host leaves the system, or if it receives no message from the host for a given interval of time (assume a failure). Otherwise, the station considers the host as *up*.

A host joining the system does not deliver those messages already discarded by the station that acknowledges its system join. Hence, we modify the *termination* condition of **causal broadcast**:
Termination. Note $s_{j,k}$ the station from which host k received the system join acknowledgment. A message m co-broadcasted by an up process is co-delivered by all up processes k for which $s_{j,k}$ did not discarded m prior to k's connection.

4 CAUSAL BROADCAST ALGORITHM

This section presents our causal broadcast algorithm, denoted *WAS*, which extends the FIFO dissemination approach [9] to mobile networks, where hosts are not static, neither reliable, and communicate through unreliable wireless channels with stations which, in their turn, communicate among themselves through reliable channels.

The algorithm is divided into three parts: (1) dissemination of application messages, (2) join/leave operations, and (3) handoff procedure to handle hosts moving between cells.

4.1 Dissemination of application messages

Hosts are the source of application messages, and stations ensure that all hosts deliver them causally. A host broadcasts an application message by sending it to the station to which it is connected. The station then forwards the message to the hosts of its cell through the wireless network, as well as to other stations through the wired network. Each station ensures that the hosts connected to it deliver application messages in causal order.

On the wireless network, message loss and FIFO ordering are handled by assigning sequence numbers to messages, and storing them in buffers for retransmission until destination nodes acknowledge them. A host uses variables seq_{h} to order messages it sends, and seq_{NC} to order messages it receives. A station uses seq_{C} to order messages it broadcasts, and stores seq_{h} and seq_{NC} of each host connected to it. In both stations and hosts, a local buffer, *RBuffer*, stores received messages until they are FIFO ordered, and *SBuffer* stores sent messages until they are acknowledged by all destination(s). A host keeps a message in *SBuffer* until its cell's station acknowledges the message. A station keeps a message in *SBuffer* until all hosts connected to it acknowledge the message.

Every application message is uniquely identified by $(\mathrm{id_h}, \mathrm{seq_h})$, where $\mathrm{seq_h}$ is the sequence number that host $\mathrm{id_h}$ associated to the message. Moreover, since cells may overlap, every message sent over a wireless network cell also piggybacks the id of this cell (id_{C}). Upon reception of the message, hosts and stations verify id_{C} and only take into account messages sent inside their cell.

Nodes (hosts and stations) regularly send acknowledge messages, containing ranges of sequence numbers to acknowledge application messages whose sequence numbers are in these ranges. Hosts do not send acknowledgments during handoffs, since they would

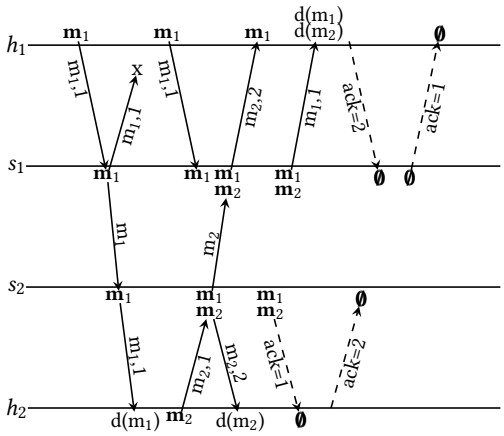


Figure 2: Broadcast of $\mathbf{m}_1$ and $\mathbf{m}_2$

acknowledge application messages received from another station, which might order messages differently.

Application messages which are delivered by all hosts are considered obsolete and should then be discarded by stations. Existing algorithms use a centralized deletion of obsolete messages [6], which has an overhead both in terms of stored messages in station *SBuffer* and the number of messages sent over the wired network: each application message m is managed by a station called $\mathrm{MSS_{init}}$, and acknowledge messages for m from each host are forwarded to $\mathrm{MSS_{init}}$. Once $\mathrm{MSS_{init}}$ received an acknowledge message from each host, it broadcasts a delete message to all stations in order to discard m. To overcome such an overhead, we have introduced a decentralized mechanism where stations discard messages using only local information: a station discards a message as soon as all hosts connected to it have acknowledged the message. Therefore, our approach does not require message exchanges between stations and a station only caches messages required by hosts of its cell.

Figure 2 shows the broadcast and delivery of two messages causally related. h_1 is connected to s_1 and h_2 to s_2. Stations s_1 and s_2 are connected by a wired channel. Hosts (resp. stations) piggyback seq_{h} (resp. seq_{C}) in application messages. *SBuffers* are represented in bold. First, h_1 broadcasts $\mathrm{m_1}$. Upon reception, s_1 forwards $\mathrm{m_1}$ to s_2 and broadcasts it in its cell, which contains h_1. Upon reception, s_2 forwards $\mathrm{m_1}$ to h_2. h_2 receives and delivers $\mathrm{m_1}$, then broadcasts $\mathrm{m_2}$ (co-broadcast($\mathrm{m_1}$) $\rightarrow$ co-broadcast($\mathrm{m_2}$)). h_2 (resp. s_2) stops transmitting $\mathrm{m_1}$ (resp. $\mathrm{m_1}$ and $\mathrm{m_2}$) upon reception of the acknowledge message regularly sent by s_2 (resp. h_2). Suppose h_1 did not receive neither $\mathrm{m_1}$ the first time s_1 broadcast it due to interferences, nor its acknowledgment. Hence, h_1 retransmits $\mathrm{m_1}$. s_1 ignores the second reception of $\mathrm{m_1}$ since it already received $\mathrm{m_1}$. Upon reception of $\mathrm{m_2}$, s_1 broadcasts it. Then h_1 receives and buffers $\mathrm{m_2}$ because the sequence number that s_1 attached to $\mathrm{m_2}$ is equal to 2, and h_1 awaits a message with seq=1. Eventually, s_1 broadcasts $\mathrm{m_1}$ again and, upon reception, h_1 delivers $\mathrm{m_1}$ then $\mathrm{m_2}$. Finally, h_1 (resp. s_1) acknowledges $\mathrm{m_1}$ and $\mathrm{m_2}$ (resp. $\mathrm{m_1}$). Hence, $\mathrm{m_1}$ and $\mathrm{m_2}$ are completely discarded from the network, i.e., removed from the buffers of all nodes.

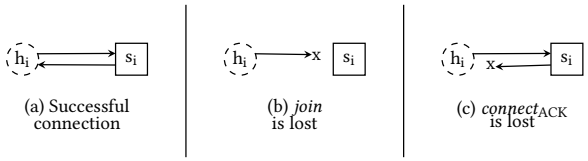


Figure 3: Host connection scenarios

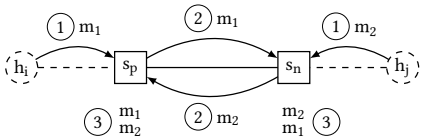


Figure 4: Sequence number assignation by stations

4.2 Join/leave the network

Joining the network. Hosts can join the network during execution. Host h_i joins the network by sending a *join* message to station s_i which then replies with the corresponding $connect_{ACK}$ message. h_i regularly retransmits *join* until receiving $connect_{ACK}$. Message exchanges between h_i and s_i can result in one of the three scenarios presented in Figure 3: (a) both the *join* and $connect_{ACK}$ message are received; or due to interferences (b) the join message or, (c) the $connect_{ACK}$ message, is lost. Since h_i cannot distinguish between (b) and (c), it cannot determine if s_i has received *join*, or not, until receiving the corresponding $connect_{ACK}$ message. Hence, h_i cannot determine if s_i registered it before receiving $connect_{ACK}$.

Host h_i might also move to another cell s_j before receiving $connect_{ACK}$ from its previous station s_i. In this case, h_i will send a *join* message to s_j, despite the fact that s_i might have also received a *join* message, and therefore registered h_i. However, a host should be connected to only one station, which is the one that received the latest *join* message sent by the host, in this case s_j.

In order to handle its multiple registrations, h_i keeps the list PS which contains the stations that might have registered its connection attempts. It identifies each of these attempts with a connection sequence number, denoted *Ses*, which it increments when changing cells. Thus, when h_i changes cells during the connection Ses, before receiving a $connect_{ACK}$ message from s_i, h_i saves the tuple (s_i, Ses) in PS. Host h_i then attaches PS to the *join* message sent in the new cell. Every station also keeps the *Ses* value corresponding to the latest connection of every host connected to it.

Station s_j replies to *join* with a $connect_{ACK}$ message which contains seq_C, the sequence number of the oldest message s_j caches in *SBuffer*. It also registers h_i and sends a *Delete* message for each tuple (s_i, Ses) in PS. Upon receiving a *Delete* message, s_i unregisters h_i, if it has been registered in the connection Ses. Such a procedure ensures that eventually h_i is only registered at s_j.

Upon reception of $connect_{ACK}$, h_i completes the connection initialization by updating seq_{NC} to seq_C, and PS to (s_j, Ses), since s_j will be the station that will control causal information related to it. h_i will then deliver messages based on seq_{NC} sequence number.

Leaving the network. A host leaves the network by sending a *leave* message containing *PS*, until a station, regardless of which one, acknowledges it. The station which receives *leave* sends a *Delete* message to each station s of the tuples (s, Ses) of PS, which will unregister h_i if registered.

4.3 Handoff procedure

A station maintains causal information related to those hosts connected to it. Hence, when a host h_i changes cell, its causal information must be transferred from its previous cell's station s_p to its new cell's station s_n. Existing handoff procedures [6][2][3] make several unrealistic assumptions, such as reliable wireless channels or that a moving host always succeeds in connecting to its cell's station before moving to another cell.

Moreover, they usually identify messages on the wired network by vector clocks, whose size is the number of stations. Hence, they are not scalable in terms of stations. The handoff procedure of our algorithm does not make such assumptions and its dissemination approach scales. It handles message losses on the wireless network as well as simultaneous connection attempts of the same host, without doing assumptions about the success of those connection attempts. Our dissemination approach scales, but requires an extra control to compare the message ordering at stations. Finally, our algorithm implements a decentralized discard approach of obsolete messages at stations, removing the message and memory overhead of centralized approaches, but also requiring an extra control when hosts change cells.

We start the handoff section by discussing the problems that the handoff procedure faces (handoff challenges), then we describe the handoff procedure algorithm itself, and finally, we give a handoff execution example.

4.3.1 Handoff challenges. We highlight the following points:

Host connections. In a real configuration, a moving host h_i cannot determine which station keeps its causal information, since it cannot distinguish between cases (b) and (c) of Figure 3. Furthermore, it might connect to several stations in a short time interval, which might lead to simultaneous h_i's handoff instances. Thus, simultaneous handoff procedures of host h_i must be handled, by ensuring that the latest handoff procedure will correctly be executed and that previous handoff procedures are ended/aborted.

Message ordering. In the dissemination phase, stations assign local sequence numbers to messages as they are received. For example, in Figure 4, at (1), h_i and h_2 broadcast m_1 and m_2 respectively. At (2), s_p receives m_1 and forwards it to s_n. Similarly, s_n forwards m_2 to s_p. At (3), s_p and s_n respectively adopt $[m_1,m_2]$ and $[m_2,m_1]$ orders. Consequently, if h_i delivers m_1 while connected to s_p and then connects itself to s_n, s_n cannot assign to h_i the sequence number $seq_{NC}=1$, because h_i would then never deliver m_2 and deliver m_1 twice. In fact, seq_{NC} is only meaningful for the last initialized connection of h_i, which is identified by Ses_{LC}, the last connection number in which h_i initialized seq_{NC}. To determine which messages h_i has delivered, s_n must therefore exchange information with s_p.

Decentralized discard mechanism of obsolete messages. A station discards a message once all hosts connected to it have acknowledged the message. This local deletion approach may lead to different *SBuffer* states of s_n and s_p: when h_i connects to s_n, s_n might have already discarded messages that s_p still caches, and that h_i did not deliver yet. For instance, in Figure 4, suppose that h_i connects to s_n before delivering m_2, but that s_n already discarded m_2 when

h_i connects to it. s_n must then recover m_2 from s_p, and h_i should deliver m_2 before delivering messages currently broadcasted by s_n.

Task of h_i :

Moving from s_p's cell to s_n's cell

1: **if** did not receive $connect_{ACK}$ from s_p **then**
2: PS ∪ = {s_p, Ses}
3: Ses++
4: send(<connect,id_h,seq_{NC},Ses,Ses_{LC},PS>) to s_n

receive <$connect_{ACK}$,seq_{h_m},seq_{C_m},Ses_m>:

5: **if** Ses==Ses_m **then**
6: seq_{NC}=seq_{C_m};seq_h=seq_{h_m};Ses_{LC}=Ses_m;PS={s_n,Ses_m}

Task of s_n :

receive <connect,id_h,seq_{NC},Ses,Ses_{LC},PS> from host h_i:

1: **if** id_h registered ∧ handoff over ∧ Ses ≥ Ses_i **then**
2: **if** Ses_{LC}==Ses_i **then**
3: use seq_{NC} as acknowledgment
4: Ses_i=Ses ; PS_i = PS
5: seq_{C_i}= determine seq_C attributed to h_i
6: **if** no message discarded from *SBuffer* to deliver **then**
7: send(<$connect_{ACK}$,id_h,seq_{C_i},Ses_i>) to h_i
8: **else**
9: Register(id_h)
10: send(<Req_1,id_h,seq_{NC},Ses_{LC},Ses>) to stations of PS

receive <Rsp_1,id_h,seq_h,m_{nd},Ses> from station s_p:

11: seq_{h_i}=seq_h
12: msg_{req}=message of m_{nd} that s_n already discarded
13: send(<Req_2,id_h,msg_{req},Ses>) to s_p

receive <Rsp_2,id_h,msg,msg_{rcv},Ses> from station s_p:

14: piggyback id_h on messages h_i has delivered at s_p
15: send to h_i messages already discarded by s_n (∈ msg)
16: **if** msg == ∅ **then**
17: seq_{C_i}= min(m.seq, m ∈ s_n.SBuffer not delivered by h_i)
18: send(<$connect_{ACK}$,id_h,seq_{C_i},Ses_i>) to h_i
19: send(<Delete,id_h,PS[i].Ses>) to stations of PS_i
20: rcv(Req_1) for stored Req_1 with highest Ses

Another point that makes the comparison of the *SBuffer* states of s_n and s_p difficult, is that s_p does not maintain information about messages it has already discarded. For example, in Figure 4, if s_p deletes m_1 once h_i acknowledged it, then when h_i moves to s_n, s_p cannot inform s_n that h_i has already delivered m_1, since it caches no information about m_1. Moreover, since stations receive messages at different times, s_n might receive messages that s_p only receives later. s_n must distinguish between messages that s_p receives during the handoff from messages that s_p already discarded (i.e. m_1).

4.3.2 Handoff procedure description. When h_i moves to s_n's cell, it sends a *connect* message to s_n that contains: the connection sequence number *Ses*, the connection sequence number Ses_{LC} of its last acknowledged connection, the sequence number seq_{NC} of the last message h_i delivered, and the list *PS* containing the stations that might register h_i.

Task of s_p :

receive <Req_1,id_h,seq_{NC},Ses_{LC},Ses>:

1: **if** current handoff and Ses>Ses_i **then**
2: save Req_1
3: **else if** Ses>Ses_i **then**
4: **if** Ses_{LC} == Ses_i **then**
5: use seq_{NC} as acknowledgment
6: m_{nd}={(id_h,seq_h) of messages h_i has not delivered}
7: Ses_i=Ses
8: send(<Rsp_1,id_h,seq_{h_i},m_{nd},Ses>) to s_n

receive <Req_2,id_h,msg_{req},Ses>:

9: msg= messages s_n requests in msg_{req}
10: m_{rcv}= messages s_p received since receive(Req_1)
11: unregister(id_h)
12: send(<Rsp_2,id_h,msg,m_{rcv},Ses>) to s_n

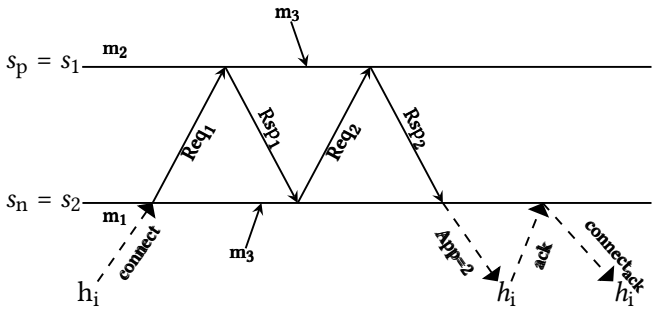


Figure 5: Handoff procedure

The pseudo-code of the handoff procedure is given by Tasks h_i, s_n, and s_p.

Upon reception of a *connect* message, s_n verifies if it has already registered h_i (line s_n.1) which happens if (1) h_i was previously connected to s_n, then tried to connect to another station but the *connect* message was lost (Figure 3.b), and then h_i tried to re-connect to s_n; (2) s_n already received the *connect* message but the $connect_{ACK}$ message was lost (Figure 3.c). Station s_n distinguishes between (1) and (2) with the help of Ses_i, since in case (1), Ses_{LC} is equal to Ses_i. In this case, h_i might have delivered messages without acknowledging them and, therefore, s_n takes seq_{NC} of h_i as an acknowledgment. In both cases, if h_i has no message to deliver which s_n discarded from its *SBuffer*, then s_n sends a $connect_{ACK}$ message to initialize the connection on h_i's side (s_n.7). On the other hand, s_n registers h_i if not registered (lines s_n.9 – s_n.10) and starts the handoff procedure.

Figure 5 shows a handoff procedure, which is a message exchange composed of three phases:

- Phase 1: detection by s_n of discarded messages that h_i has not delivered. Messages Req_1 and Rsp_1 are exchanged between s_p and s_n in this phase.
- Phase 2: detection by s_n of messages that h_i has not delivered among messages that s_n caches. Messages Req_2 and Rsp_2 are exchanged between s_p and s_n in this phase.
- Phase 3: initialization of the connection between s_n and h_i.

Phase 1: s_n starts this phase by sending Req_1 to the previous stations included in PS that might register h_i (line s_n.10). Note that

(1) all messages not delivered by h_i that s_n discarded were received by s_n before *send(Req$_1$)*, because s_n discards no message after the reception of h_i's *connect* message unless h_i acknowledged it; (2) the FIFO dissemination approach on the wired network ensures that, upon reception of Req_1, s_p receives all messages that s_n received before sending Req_1. Upon reception of Req_1, station s_p uses seq_{NC} piggybacked onto Req_1 to identify the messages that h_i has not delivered yet (line s_p.8), and sends their respective id via Rsp_1.

The FIFO dissemination approach on the wired network ensures that, upon receiving Rsp_1, s_n received all messages that h_i could have delivered in previous connections. s_n might have already discarded some of those messages. s_n identifies the messages it discarded but that h_i has not delivered (lines s_n.12), and requests them in Req_2 message. Then, s_p piggybacks these messages onto the Rsp_2 message, keeping the same order as in its *SBuffer* (line s_p.13).

Simultaneous handoff procedure instances for h_i are handled sequentially. If Req_1 messages are received during a handoff execution, the one with the highest *Ses* value is kept pending provided that it is newer than the current handoff's *Ses* value. The station will handle that Req_1 at the end of the current handoff (line s_p.20). Req_1 messages with lower *Ses* values concern handoffs of previous connection attempts and are discarded. At the end of the handoff s_n sends a *Delete* message containing the handoff's *Ses* value (line s_p.2) to the stations of PS so that those stations unregister h_i.

Phase 2: The FIFO dissemination approach on wired channels guarantees that messages that h_i could deliver when connected to s_p are received by s_n at latest at Rsp_1, since Rsp_1 was sent after that s_n sent *connect*, and h_i delivers no message from s_p after changing cell (after sending *connect*). Messages not delivered by h_i that s_n receives before sending Req_1 are identified by s_p in Rsp_1. Phase 2 identifies messages that s_n receives between *send(Req$_1$)* and *receive(Rsp$_1$)* that h_i has not delivered.

The FIFO dissemination on wired channels also guarantees that messages received by s_n between *send(Req$_1$)* and *receive(Rsp$_1$)* are surely received by s_p between *receive(Req$_1$)* and *receive(Req$_2$)*. s_p saves the id of such messages and sends this list of ids to s_n in Rsp_2 message (lines s_p.9 – s_p.12).

Upon reception of Rsp_2, s_n determines which messages h_i has not delivered among those received before Rsp_1. The messages are those (1) s_p identified as not delivered by h_i (line s_p.8), (2) s_p received between the receptions of Req_1 and Req_2 (line s_p.12). On the other hand, h_i has already delivered all the other messages s_n received before Rsp_1. Moreover, messages that s_n receives after Rsp_1 are not delivered by h_i because the FIFO dissemination approach on wired channels ensures that all messages received by s_p before it sent the Rsp_1 message were also received by s_n before *receive(Rsp$_1$)*.

Phase 3: Assigning a sequence number to h_i is not sufficient to identify all messages already delivered by h_i. For example, in Figure 4, if h_i delivered m_1 before connecting to s_n but did not deliver m_2, then s_n must give to h_i the sequence number 0 (seq_{NC} = 0), so that it will deliver m_2. However, without additional control, h_i would then also deliver m_1 again. To prevent h_i of delivering the same messages twice, s_n adds h_i's id to the messages h_i already delivered but which are still cached in s_n's *SBuffer*(line s_n.14), and, upon receiving them, h_i will only increment seq_{NC} and not deliver them again.

Moreover, s_n must send to h_i messages identified at Phase 2 that it already discarded but that h_i did not deliver. s_n sends these messages to h_i, ordered as in *msg*, also piggybacking (id_{h_i}, Ses_i) that identify the handoff procedure instance. Once h_i acknowledged all of them, or if h_i has no message to deliver that s_n discarded (s_n.16), then s_n concludes the handoff by sending a $connect_{ACK}$ message to h_i with seq_{C_i}, the sequence number of the oldest message in s_n's *SBuffer* that h_i has not delivered (line s_n.18). At its side, h_i ends the handoff by setting seq_{NC}, seq_h, and Ses_{LC} (line h_n.4).

4.4 Handoff example

Figure 5 presents the handoff executed when h_i, previsouly connected to s_p, tries to connect to s_n in the configuration of Figure 4. For better readability, we assume that no other handoff procedure takes place simultaneously for h_i. At the beginning of the handoff s_p has discarded m_1, s_n discarded m_2, and h_i delivered m_1. Both stations receive m_3 during the handoff.

Host h_i sends a *connect* message to s_n, which contains seq_{NC}=2, since h_i delivered m_1. Upon reception of the *connect* message, s_n sends Req_1 to s_p with seq_{NC}=2. When receiving Req_1, s_p concludes that h_i has not delivered m_2 and replies with Rsp_1 = {{id(m_2)}, seq_h = 1} (seq_h=1 since h_i already broadcasted m_1). s_n requests then m_2 via Req_2, since it has already discarded m_2. s_p replies with Rsp_2 containing the requested message ({m_2}) and the list of messages received between Rsp_1 and Rsp_2 ({id(m_3)}). Finally, s_p unregisters h_i. s_n determines with Rsp_2 which messages of its *SBuffer*={m_1, m_3} h_i has delivered. s_n received m_1 before Rsp_1, and s_p did not identify m_1 as not delivered by h_i. Hence, h_i already delivered m_1 and s_n adds h_i's id via m_1. In addition, h_i must first deliver m_2 before delivering m_3. Thus, s_n resends m_2 received from s_p with seq_C=0 to h_i. Finally, s_n discards m_2 once h_i acknowledged it, assigns seq_{C_i}=3 to h_i, since h_i delivered m_1 and m_2, and sends $connect_{ACK}$ to h_i. Upon reception of $connect_{ACK}$, h_i sets seq_{NC}=3.

4.5 Host failures

Hosts can fail temporarily or permanently and stations handle such failures. The duration of temporal failures should be bounded in time. In fact, a station does not discard a message until all hosts of its cell, including the faulty one, have acknowledged the message. Hence, a long temporal failure would increase the number of messages a station broadcasts, which in turn would increase the station's cell's message collision rate. The latter would then decrease the throughput, which could reach the point where messages are delivered more slowly than new messages are broadcasted, degrading the cell forever. Thus, stations control their cell's collision rate and a station unregisters a faulty host before this rate becomes too high. A station considers that a host is faulty when it does not receive any message from the host during a given time interval, or if the message collision rate becomes too high due to the lack of acknowledgments from the host.

Few variables of the host's persistent local storage should be restored when it recovers from a temporal failure: seq_h, seq_{NC}, *Ses*, and Ses_{LC}, and unacknowledged messages broadcasted by the host before its failure. Note that the number of these messages is quite small since messages are acknowledged very fast. A host

saves seq_{h} (resp., seq_{NC}) when broadcasting an application (resp., acknowledge) message, *Ses* when changing cell, and Ses_{LC} when the host receives the confirmation that the station registered it. Upon recovering, the host restores these variables and sends a *recover* message to the station of its cell. However, since a faulty host can move during its temporal failure or stay faulty for a long time, this station might not keep the host's causal information. If the station still registers the host, it replies to the host with a $connect_{\text{ACK}}$ message. Otherwise it broadcasts a $recovery_{\text{req}}$ to stations, which reply with either the host's causal information, or a message that notifies that they do not store the host's causal information. If no station maintains the host's causal information, the end of the recovery procedure is similar to the join procedure, otherwise to a cell changing.

Summing up, our algorithm tolerates permanent and transient failures, requiring few persistent information. Based on wireless message loss rate and timeouts, a station removes from its memory a host that permanently or temporarily failed. We point out that, inherent to wireless networks, interferences constrain the effectiveness of transient fault tolerance.

5 PERFORMANCE EVALUATION

Experimental setup. Experiments were conducted on INET, a network simulator implemented on OMNeT++ [21]. INET offers communication layers (e.g., TCP/UDP/Ethernet/IPv4/MAC), node mobility, node failures, and network interferences in wired and wireless networks.

Since no causal broadcast in mobile networks has been proposed yet, we compare our algorithm, denoted *WAS*, with the one proposed by Chandra and Kshemkalyani [6], denoted *CK*, which we have described in Section 6. We extended *CK*, which provides a causal multicast algorithm, to causal broadcast.

Stations are placed to ensure a complete area coverage with a minimum intersection of cells. Hosts are placed randomly in each cell at initialization. Antennas have a communication range of 120m and a bandwidth of 20Mb/s. Stations are connected by a wired network organized into a tree of degree 3 whose links have a bandwidth of 100Mb/s and a delay of 10ms. Application messages have a size of 100 bytes and are encapsulated in IPv4/MAC packets, whose header has 8 (resp., 20) bytes for UDP (resp., TCP). Therefore, an UDP (resp., TCP) packet has an overhead of 20(IPv4)+20(MAC)+8(UDP)=48 (resp., 60) bytes. UDP is used for communication on the wireless network, while TCP on the wired network. Each host broadcasts application messages following a Poisson distribution. Hosts move in a straight line with a speed of 5km/h≈1.39m/s inside the area covered by stations, and change direction every 5 seconds.

Experimental results concern three evaluations: (1) scalability comparison between *WAS* and *CK*, (2) comparison between a centralized and decentralized message discarding, (3) execution of *WAS* in a scenario with faulty hosts.

5.1 Scalability

Throughput and delivery delay. The first experiment, whose results are shown in Figure 6, evaluates the maximal throughput when the number of hosts per cell increases. The experiment contains 10 stations and a total number of hosts that varies from 100 to 400 (x-axis). Results, presented in a logarithmic scale, show that *WAS* has a much higher (x10-20) throughput than *CK*, and that the throughput of *CK* decreases faster than *WAS*. In a system containing 400 hosts, the maximal throughput of *WAS* is more than 20x higher than *CK*. The throughput of *CK* is bounded mostly by the fact that a station only sends an application message to a host once the latter has acknowledged all the message's dependencies. Consequently, hosts send acknowledge messages very frequently, which negatively impacts performance because of a higher message collision rate on the wirless network. Moreover, *CK* has a delivery delay - the delay between broadcast(m) and deliver(m) - 2 times higher than *WAS*, because a station waits that a host acknowledges a message's dependencies before sending it to the host.

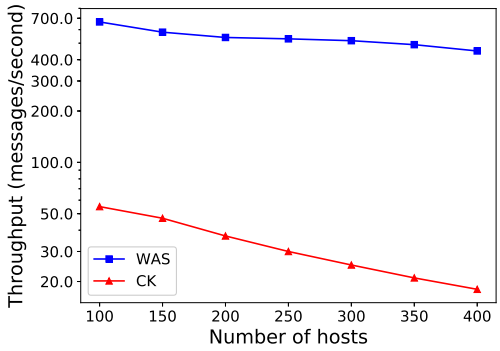


Figure 6: Throughput in function of hosts per cell

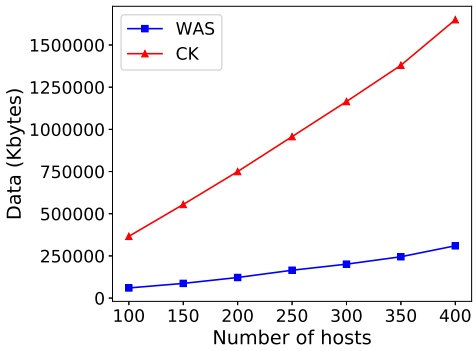
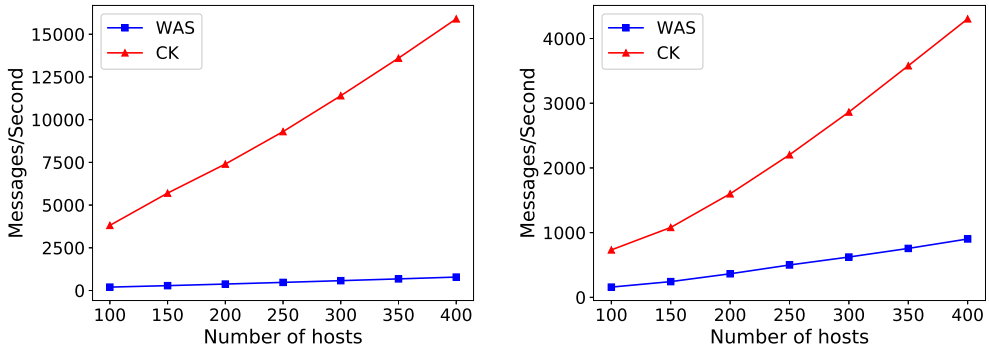


Figure 7: Sent data (Kbytes)

The second experiment measures the size and number of messages, evaluated at the IPv4 level, when the number of hosts increases. Results are shown in Figures 7 and 8 respectively. The number of stations is adapted to keep a ratio of 20 hosts/cell. 20 messages are broadcasted per second in the system.

Number of sent messages. Figure 8 shows that *WAS* sends much fewer messages on both the wired and wireless networks. Moreover, the number of messages sent by *CK* increases much faster than the number of messages sent by *WAS*. *WAS* sends fewer messages on the wireless network because (1) hosts acknowledge messages less often than *CK* (20x), (2) hosts buffer messages at



(a) Messages sent over the wireless network **(b) Messages sent over the wired network**

Figure 8: Sent messages in the network

reception following seq_{NC} piggybacked on messages, contrarily to *CK* where hosts do not buffer messages since stations only send a message *m* to a host once the host can causally deliver *m*. Hence, stations must retransmit messages less often than with *CK* (x5). On the wired network, *CK* sends more messages due to its centralized approach to discard obsolete messages. *WAS* implements a decentralized mechanism which requires no message exchange to discard obsolete messages. We point out that *CK* sends much fewer messages on the wired network than theoretically expected, because acknowledge messages of *CK* are small, and TCP groups many of them in a single packet.

Amount of sent data. Figure 7 shows that *WAS* sends a lower amount of data than *CK*. On the wireless network, this is mostly due to acknowledge messages. Even though these messages contain only a few integers, they have an additional size of 48 bytes because they are encapsulated in UDP/IPv4/Mac packets. However, only a few acknowledge messages can be grouped into one single packet since the station will not send the next messages to deliver until the current ones are acknowledged. On the wired network, acknowledge and *delete* messages are grouped by TCP, which mostly removes the encapsulation overhead. However, those many acknowledge and *delete* messages scale up fast. Moreover, with *CK* stations piggyback a vector of size N (N=number of stations) on application messages sent over the wired network, and that vector rapidly takes much space when the number of stations increases. *WAS* only piggybacks a few integers on application messages.

5.2 Decentralized discard mechanism

This section compares our decentralized discard approach, used by *WAS*, with the existing centralized discard approach [6].

In the third experiment, 200 hosts are distributed over 10 cells, the wireless network has a bitrate of 1Mb/s, and 35 messages are broadcasted per second for 300s. Figure 9 shows the number of messages that stations store in their respective SBuffer. Curve *Max* shows the maximum number of messages cached in a stations' SBuffer, i.e., approximately the number of messages each station would store with a centralized discard approach. Curve *Avg* shows the average number of messages a station stores in its sending buffer, and curve *Deviation* gives the standard deviation between the average and the number of messages each station caches. The curves *Avg* and *Deviation* do not take into account the *SBuffer* of the station that stores the most messages, in order to compare both curves with the *Max* curve.

The comparison of curves *Avg* and *Max* of Figure 9 shows that the number of messages cached by stations can vary a lot. Such a variation depends on the message loss rate in the station's cell: the higher the message loss rate, the longer a station caches a message, since lost messages must be retransmitted. The message loss rate depends on the number of messages to broadcast as well as the position of hosts in the network. The probability of message collision is higher in areas where two cells overlap because the respective stations send messages over their cells that might collide. Similarly, areas with a high density of hosts have a higher message loss rate. The *standard deviation* is low, mostly around 10 messages, except for a short period around 70s where a heavily loaded cell degrades its adjacent cells. Hence, the number of messages a station stores in *SBuffer* is mostly close to the average for all stations, except for some stations whose local characteristics make their send buffer grow temporarily. In a decentralized message discard approach, message loss rate and failing hosts only have a local impact. The comparison of curves *Avg* and *Max* shows that with a decentralized message discard approach, stations store up to 4 times fewer messages than with a centralized one, and that, on average, stations store 40-50% fewer messages.

Finally, a host that fails stops acknowledging messages. Hence, the station which the host is connected to will stop discarding messages, and Figure 10 shows that, in presence of host failures, the station to which the faulty host is connected then caches many more messages than the other stations (8-10x more). Hence, the decentralized discard approach caches up to 8-10 times fewer messages on stations in presence of host failures.

5.3 Transient host failures

The last experiment, whose results are presented in Figure 10 measure the impact of transient host failures on *WAS* in a system containing 10 stations and 200 hosts (20 hosts per station), a wireless network bitrate of 1Mb/s, and where 15 messages are broadcasted per second. The first host fails at t=10s for 5 seconds, then each 30 seconds another host fails, and the fault duration increases by 2 seconds at each failure. In total, 9 hosts fail, the first failing at t=10s

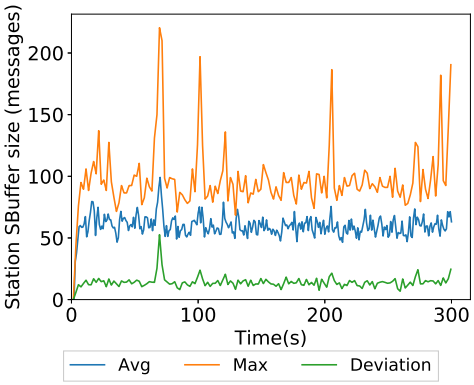


Figure 9: Messages in station sending buffers

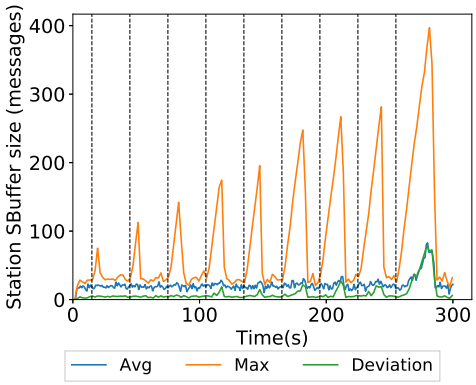


Figure 10: Messages stations cache when hosts fail

for 5s, the second at t=40s for 7s, and so on. When a host fails it stops acknowledging messages. The number of messages cached in the *SBuffer* of the station that registers the faulty host then grows. Hence, we measure the impact of transient failures through the number of messages cached in the *SBuffer* of that station.

Curve *Max* shows the maximum number of messages cached in a station's SBuffer which is, during failures, the number of messages cached by the station at which the faulty host is registered. Curve *Avg* shows the average number of messages a station stores in its SBuffer, and curve *Deviation* gives the standard deviation between the average and the number of messages each station caches. In order to evaluate the impact that a cell containing a faulty host has on the other cells, the former is not taken into account in the computation of *Avg* and *Deviation*. Vertical dashed lines represent a host crash.

During each failure, the number of messages cached by the station that registers the faulty host linearly increases. Those messages are also broadcasted by that station. Nevertheless, the number of cached messages sharply decreases once the host recovers, showing that, very fast, the host receives the missing messages and the cell rapidly reaches the same message load it had before the failure.

Curve *Avg* shows that, on average, a faulty host has a low impact in the number of messages stored by the other stations, except for the last failure occurring at t=255s.

Curve *Deviation* also shows that the increasing size of *SBuffer* of the faulty host's station has no impact on other cells, as long as the *SBuffer* does not become bigger than 150-200 messages. Once the *SBuffer* exceeds that size, the faulty host's station begins to degrade adjacent cells that overlap with it. In fact, the station broadcasts application messages and retransmits messages not acknowledged by the faulty host, thus increasing the number of messages sent by the station. This leads to an increasing number of message collisions in the cell, including the areas where the cell overlaps with other cells. Hosts in those overlapping areas, connected to other stations, will receive fewer messages, because of this higher message collision rate. Hence, they will deliver messages more slowly, increasing the number of messages broadcasted by the neighboring stations of the faulty host's cell. During the last crash occurring between t=250s and t=273s, the 3 adjacent cells of the faulty host's cell are impacted, explaining why the average size of the *SBuffer* increases. Moreover, contrarily to previous failures where the faulty host takes less than a second to acknowledge messages, the host takes 7 seconds to acknowledge all messages. Therefore, the failure of a host first and mostly has an impact in the cell in which it occurs and afterwards in adjacent cells when its cell's station stores more than 150-200 messages. Nevertheless, such an impact rapidly disappears once the host recovers.

In conclusion, experiments confirm that *WAS* is more scalable than *CK* in terms of the number of hosts per cell, as well as in terms of total hosts and/or stations. *WAS* sends much fewer messages than *CK* both on the wired and wireless network, the amount of sent data is also much lower, and *WAS* has half the delivery delay of *CK*. Second, the decentralized message discard mechanism of *WAS* caches much fewer messages than *CK*, particularly during host failures. Finally, in *WAS*, the impact of a transient host failure is sharply absorbed after the faulty host recovers.

6 RELATED WORK

Charron-Bost proved [7] that without additional assumptions on the system, the size of the information required to causally order messages grows linearly with the number of nodes of the system. Therefore, solutions based on logical clock vectors [8][13][4] are not suitable to huge mobile networks since they are not scalable.

Plausible clocks [19], Bloom filters [18], and Probabilistic clocks [14] have constant size and ensure causal order with high probability. However, even though they greatly reduce causal control information in networks with a large number of nodes, messages might be delivered out of causal order.

Hierarchical approaches [1] group nodes into clusters and logically organizes them in a tree. Causal information is handled only at the cluster level. However, clusters must be reorganized in presence of nodes churn and a node moves only inside its own cluster. Hence, such a solution cannot be applied to mobile networks because hosts move between cells/clusters and join/leave the network.

Many causal dissemination protocols [5][16][15][20], exploiting message propagation and forwarding over reliable FIFO links on overlay networks, have been proposed in the literature. They do not require any causal information since messages are implicitly causally ordered at reception. A static tree is used in [5] to disseminate messages while, by using scalable data structures, [16][15]

extend [5] protocol for dynamic systems. Nevertheless, the considered dynamics of the system cannot be applied to mobile networks, because every new channel must be initialized by message exchange through already initialized channels. Consequently, a path of initialized channels must always connect each pair of nodes, which is not always the case when a host moves to a new cell without having initiated the connection with the latter.

In [20], a reliable causal multicast is presented where nodes maintain only local metadata about their neighborhood, being, thus, scalable. The algorithm tolerates faults and outperforms other multicast causal algorithms with local views, but channels are assumed to be static.

Several works [6][17] [2] [3] [12] have proposed causal multicast for mobile networks.

Chandra and Kshemkalyani [6] consider a dynamic system composed of fixed stations and mobile hosts. For each connected host h, a station maintains information to control causal order on behalf of h. When a node h moves to a new station, its information is transferred from the previous station to the new one. A node can leave its previous station only after the new station has acknowledged the reception of such information which implies some constraints on the mobility model. Moreover, the algorithm implements a centralized message discarding of obsolete application messages, which has an overhead both in terms of stored messages in station *SBuffer* and number of messages sent over the wired network: each application message m is managed by a station called MSS_{init}, and acknowledge messages for m from each host are forwarded to MSS_{init}. Once MSS_{init} received an acknowledge message from each host, it broadcasts a delete messsage to all stations in order to discard m.

In [17], messages piggyback only direct dependencies. Such an approach copes with the dynamics of mobile networks since causal information does not depend on node identifiers. However, every node, including mobile hosts that have memory limitations, maintains a matrix of size N^2, where N corresponds to the maximum number of nodes in the system. Moreover, the information piggybacked on messages grows with the number of concurrent messages In [2], the authors propose a multicast protocol that tolerates a dynamically changing system membership. On the other hand, host mobility is not supported by the algorithm, which does not implement any handoff procedure. Contrarily, [3] and [12] present causal multicast protocols that tolerate node mobility among stations, but both consider that wireless channels are FIFO and reliable, the connection protocol is reliable, and hosts do not fail, which are not realistic assumptions.

7 CONCLUSION

We have presented in this article a causal broadcast algorithm tailored to the features and dynamics of mobile networks. The latter include host mobility, dynamic host membership, unreliable dynamic wireless channels, memory and computing constraints of mobile hosts, scalability issues due to the high number of mobile hosts and stations, and mobile host failures. Messages piggyback few causal information. Mobile hosts have a low memory footprint while stations have a memory footprint that grows linearly with the number of locally connected mobile hosts. Stations discard obsolete messages with only local information, removing the message exchange between stations used by centralized message discarding approaches.

Performance results from simulations done on OMNeT++/INET show that our algorithm has a much lower message overhead, delivery delay, and caches fewer messages than a representative algorithm adapted to provide causal broadcast [6]. Furthermore, the decentralized approach to discard obsolete messages of our algorithm results in much fewer messages cached by stations, as well as much fewer messages sent on the network compared to a centralized approach. Finally, performance results show that hosts that temporarily fail fastly catch up after recovering, and that the decentralized discard approach of obsolete messages mostly limit the impact of host failures to the cells in which those failures occure.

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APPENDIX - PROOF OF THE ALGORITHM

Proof when nodes never move between cells

Theorem 1: *WAS* ensures causal broadcast in mobile networks when hosts do not move between cells. *Validity.* A station initially disseminates only messages co-broadcasted by hosts connected to it. Hence, all application messages disseminated among stations are messages co-broadcasted by a host. Moreover, a host only co-delivers messages that the station to which it is connected sends to it. Hence, hosts only co-deliver messages co-broadcasted by hosts. *Integrity.* The wired network connecting stations is FIFO and reliable. Hence, on the wired network, our dissemination approach ensures that every station receives each message once and that the message is causally ordered at reception. Each station then attributes a unique sequence number to each message it receives and sends them to the hosts of its cell. A host delivers messages in increasing sequence number. Thus, a host that delivers a message *m* will never deliver *m* again, since its local sequence number will be greater than the sequence number of *m*.
Causal order. As explained above, messages are causally ordered upon their reception at stations. A station attributes an increasing sequence number to each message following its arrival time. Hence, if $m \rightarrow m'$, then stations receive m before *m'*, and, therefore, $m.seq < m'.seq$. Moreover, hosts deliver messages in increasing sequence number. Hence, hosts deliver messages causally ordered. *Termination.* A host h_i that joins the system is not considered up until the station s_i to which h_i connects itself receives h_i's join message. Upon reception of the message, s_i attributes to h_i the sequence number of the application message it caches with the lowest sequence number. Moreover, s_i retranmits the join acknowledgment as well as every cached application message until h_i acknowledged each pf them (i.e., after having delivered it), or s_i considers h_i as down. Hence, all messages that s_i did not discarded upon the reception of h_i's join message will be delivered by h_i, given that h_i remains an up process.□

Proof when nodes move between cells

Now we show that *WAS* ensures causal order even when hosts move between cells.

Lemme 1: When a host h_i leaves the cell of station s_p and connects to station s_n, then s_n recovers those messages it has previously discarded and that h_i has not delivered yet.
First, s_n does not delete messages after s_n.recv(connect) from h_i unless h_i acknowledges them. On the other hand, messages not delivered by h_i but discarded by s_n are received by s_n before s_n.recv(connect). Station s_n recovers those discarded messages during the handoff with s_p: (1) Phase 1 composed of Req_1 and Rsp_1 identifies them. The reliable FIFO channels connecting stations ensure that, when s_p receives the Req_1 message sent by s_n, it received all the messages that s_n received prior to s_n.recv(connect). s_p replies to Req_1 with Rsp_1 which contain msg, the list with the ids of messages h_i have not delivered among those s_p received before Req_1. (2) Phase 2 composed of Req_2 and Rsp_2 recovers at s_n the messages of msg that s_n has discarded. In Req_2, s_n requests to s_p the messages of msg_{nd} it has already discarded, and s_p sends them to s_n in Rsp_2. Thus, at the end of Phase 2, s_n buffers all messages it has discarded prior to the connection of h_i that it has not delivered yet.

Lemme 2: Upon reception of Req_1, s_p received all messages that h_i has delivered.
h_i stops to deliver messages once it sends a connect message to s_n, and will only deliver messages again after receiving $connect_{ACK}$ from s_n. Moreover, s_n sends Req_1 to s_p after receiving connect from h_i. Hence, s_p receives Req_1 after that h_i sent connect, i.e., after h_i stopped to deliver messages. Since s_p handles the causal information of h_i, the latter only delivers messages already received from s_p. Hence, messages that h_i delivered are received by s_p at latest when s_p receives Req_1.

Lemme 3: Upon reception of Rsp_1, s_n received all messages that h_i has delivered.
Following Lemme 2, upon reception of Req_1, s_p received all messages that h_i delivered. s_p forwarded all those messages to s_n (FIFO dissemination). Moreover, s_p replies to Req_1 by sending Rsp_1 to s_n. The FIFO dissemination ensures that, upon the reception of Rsp_1, s_n received all messages that s_p forwarded prior to s_p's reception of Req_1. Therefore, upon the reception of Rsp_1, s_n received all messages that s_p broadcasted until its reception of Req_1, i.e., messages that h_i might delivered.

Lemme 4: The union of the lists m_{nd} of Rsp_1 and msg_{rcv} of Rsp_2 contain the id of messages that h_i did not deliver among the messages that s_n receives before the reception of Rsp_1.
Following Lemme 2, h_i did not deliver any message that s_p receives between Req_1 and Req_2. msg_{rcv} contains those messages. Among the messages that s_p received before the reception of Req_1, those not delivered by h_i are contained in m_{nd}. Therefore, $m_{nd} \cup msg_{rcv}$ contains the list of messages (or their id) not delivered by h_i among the messages s_p received upon the reception of Req_2. The FIFO dissemination ensures that upon reception of Req_2, s_p received all messages that s_n received upon reception of Rsp_1. Hence, $m_{nd} \cup msg_{rcv}$ contains the list of messages or their id not delivered by h_i that s_n received upon the reception of Rsp_1.

Lemme 5: Messages that h_i has not delivered are those that s_n receives before Rsp_1 identified or contained in $m_{nd} \cup msg_{rcv}$ and the messages s_n receives after Rsp_1.
Following Lemme 4, messages that h_i has not delivered among the ones s_n receives before Rsp_1 are those contained in $m_{nd} \cup msg_{rcv}$. Following Lemme 3, messages that h_i delivered are received by s_n upon its reception of Rsp_1. Hence, all messages s_n receives after Rsp_1 are not delivered by h_i.

Lemme 6: To respect causal order, h_i must first deliver the messages of msg_{rcv} of Rsp_2, i.e., messages that s_n discarded before the connection of h_i but that h_i did not deliver, before delivering messages currently broadcasted by s_n.
Hosts acknowledge messages whose sequence number is lower than their seq_{NC}. Hence, messages that s_n discards have a lower sequence number than messages s_n still caches. h_i must, therefore, first deliver messages of msg, since hosts deliver messages in increasing sequence number.

Theorem 2: *WAS* ensures causal broadcast in mobile networks where hosts move between cells.
Following Theorem 1 *WAS* ensures causal broadcast in mobile networks where hosts do not move between cells. We will show that the handoff procedure of *WAS* ensures that the causal information of a host that moves to a new cell is transmitted to the new cell's station and, therefore, the new cell's station also ensures causal

broadcast for the moving host.

Validity. The validity of causal broadcast does not change when hosts move between cells. Hence, the validity proof of Theorem 1 holds.

Integrity. Following Theorem 1, hosts co-deliver a message at most once when not changing cell. Let's show that when a host h_i moves from the cell of station s_p to the cell of station s_n, that s_n will identify the messages that h_i did already deliver, and that h_i will not deliver those messages again. Following the corollary of Lemme 5, messages that s_n caches that h_i has already delivered are those that s_n receives before Rsp_1 that are not identified in $m_{nd} \cup msg_{rcv}$. «««< HEAD s_n broadcasts these message piggybacking h_i's id on them, and h_i does not deliver them, but only increments its sequence number to deliver the next messages sent by s_n. Moreover, following Lemme 5 messages that s_n receives after Rsp_1 are not delivered by h_i. Therefore, h_i will not deliver again messages it has already delivered. Hence, h_i will not deliver any message twice, i.e., h_i will deliver a message at most once.

Causal order. Theorem 1 shows that causal order is ensured when hosts do not change cell. Let's show that when a host changes cell, no application message is lost and that the host delivers them respecting causal order. Following Lemme 6, h_i must first deliver messages it has not delivered yet but that s_n discarded prior to its connection. Following Lemme 1, s_n recovers those messages at s_p which orders them in the list msg_{rcv} of Rsp_2 following their reception order. Moreover, s_n sends them to h_i before sending to h_i messages it currently broadcasts. Therefore, h_i will deliver those messages in FIFO (and consequently in causal) order. Following the corollary of Lemme 5, messages that s_n caches that h_i has already delivered are the messages that s_n receives before Rsp_1 that are not identified in $m_{nd} \cup msg_{rcv}$. s_n piggybacks h_i's id on those messages, and h_i does not deliver them, but only increments its sequence number to deliver the following messages sent by s_n. Hence, all messages which piggyback h_i's id have been already delivered by h_i. For all other messages cached by s_n, h_i will deliver them in increasing sequence number order. Hence, h_i first delivers messages not cached anymore by s_n, then it delivers the messages cached by s_n in increasing sequence number order, i.e., causally ordered.

Termination. Theorem 1 shows that the termination is ensured when hosts never move between cells. Let's show that an up host that changes cell will co-deliver all application messages. Note that a host that delivers no message because it changes to often its cell would eventually be considered as down by the station registering it. Therefore, periodically, hosts are supposed to be long enough inside a cell in order to deliver outstanding application messages. Let's consider that host h_i moves from the cell of station s_p to the cell of station s_n. Following Lemme 1, s_n recovers messages it discarded among those h_i has not delivered yet in the list msg_{rcv} of Rsp_2. s_n then sends those messages to h_i. Moreover, after receiving the connect message from h_i, s_n will not discard any message unless it considers h_i as down, and will retransmit them periodically until h_i acknowledges them. Hence, the handoff procedure ensures that s_n recovers and sends to h_i all messages it discarded that h_i has not delivered, and for all other messages not delivered yet by h_i, s_n caches them and will retransmit them until h_i acknowledged them.□

Proof that handoffs finish and that the most recent will execute

Lemme 8: PS that host h_i appends on connect messages contains the station that holds h_i's causal information, as well as the corresponding connection sequence number.

Station s_n only sends a $connect_{ACK}$ to h_i once it received h_i's causal information. Hence, h_i knows, when receiving a $connect_{ACK}$ message from s_n during the connection Ses_k, that s_n maintains its causal information during the connection with sequence number Ses_k. Hence, h_i sets PS to (s_n, Ses_k) when it receives a $connect_{ACK}$ message from station s_n during the connection Ses_j. Otherwise, when h_i changes cell, it appends the tuple (s_i, Ses_j) on PS when it connects to station s_i with the connection sequence number Ses_k. Hence, PS contains the identifier (s_n, Ses_k) of the last confirmed connection that maintained its causal information, as well as the tuples (s_i, Ses_j) of later connections that might maintain its causal information.

Lemme 9: All connections not included in PS that h_i appends on connect messages are either finished or will be finished by a Delete message.

h_i adds the tuple (s_i, Ses_j) to PS each time it changes cell and connects to station s_i with connection sequence number Ses_j. It sets PS to (s_n, Ses_k) when receiving a $connect_{ACK}$ from s_n during the connection Ses_k. Hence PS contains the connection identifiers since the last connection (s_n, Ses_k) in which h_i received a $connect_{ACK}$. When sending a $connect_{ACK}$ message, s_n also sends a Delete message for all connections of PS. A non finished connection (s_i, Ses_j) of PS will then be finished by station s_i at reception of the Delete message. Hence, all connection not contained in PS are either finished or will be finished by a Delete message.

Lemme 10: If several handoffs occure simultaneously for the same host, then the station that started the handoff with the highest session sequence number, i.e. the handoff of the most recent connection, will eventually be the only station that registers the host and holds its causal information.

Consider host h_i that changes cell several times in a short time interval, leading to a sequence (s_j, Ses_j), $i < j < k$ of handoffs occuring simultaneously. We show that station s_k will eventually hold h_i's causal information with th connection session number Ses_k. Following lemme 8, the causal information of h_i is maintained in one of the connection (s_i, Ses_i) contained in PS. s_k sends a Req_1 message to station s_i for each connection (s_i, Ses_i) of PS. The station that maintains the causal information of h_i either receives $Req_{1,k}$ from s_k or from another station s_j, $i < j < k$. If it first receives $Req_{1,k}$ from s_k, then it will send the causal information of h_i to s_k, and s_k will, at the end of the handoff (s_n.19), send *Delete* messages to finish all connections of PS. Therefore, s_k will maintain the causal information of h_i and all other stations will unregister h_i. If the station that holds h_i's causal inforamtion first receives the $Req_{1,j}$ message from another station s_j, $i < j < k$, then s_j will receive the causal information of h_i. However, following lemme 8 s_j the connection for which s_j does the handoff is included in PS. Hence, s_j will receive the $Req_{1,k}$ message from s_k. If upon reception of $Req_{1,k}$ the handoff of s_j is not finished, it will cache $Req_{1,k}$ until the end of the handoff where it will handle it. If the handoff is finished, it will handle $Req_{1,k}$ directly. Hence, s_k will eventually receive the causal

information of h_i. Moreover, s_k will send a Delete message to close all conection of PS, and following Lemme9, all connections not included in PS are finished or will be finished by a Delete message. Hence, eventually s_k will be the only station that registers h_i and it will hold h_i's causal information.

Theorem 3: Each handoff eventually ends.
Following lemme10, if several handoffs occure for the same host simultaneously, the station that initiated the most recent handoff will eventually hold the host's causal information. If a handoff is not concurrent with another one, it will execute normally. Hence, each handoff eventually ends. □