A TEMPORAL SYNCHRONIZATION MECHANISM FOR REAL-TIME DISTRIBUTED CONTINUOUS MEDIA

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Abstract: The preservation of temporal relations for real-time distributed continuos media is a key issue for emerging multimedia applications, such as Tele-Immersion and Tele-Engineering. Although several works try to model and execute distributed continuous media scenarios, they are far from resolving the problem. The present paper proposes a viable solution based on the identification of logical dependencies. Our solution considers two main components. First, it establishes a temporal synchronization model that expresses all possible temporal scenarios for continuous media according to their causal dependency constraints. The second component consists of an innovative synchronization mechanism that accomplishes the reproduction of continuous media according to its temporal specification. We note that the present work does not require previous knowledge of when nor for how long the continuous media of a temporal scenario is executed.

1 INTRODUCTION

The subject of synchronization for distributed continuous media addresses the problem of preserving temporal relations among streams (continuous media) having geographically distributed sources. The synchronization in this kind of media is carried out without previous knowledge of when or for how long the streams are or will be executed. Several works attempt to resolve this problem. We can group them according to their synchronization model into two broad categories: *synchronous* and *asynchronous*. The main difference between these categories relates to whether they consider in some way or not a *common reference* (virtual or physical clocks, shared memory, off-line synchronization, etc). While a common reference is present in the synchronous category, it is absent in the asynchronous one. Most works fall into the synchronous category (Allen, 1983; Pantelis et. al, 2000; Colin, 1998). These works usually try to answer the synchronization problem by measuring the period of physical or virtual time elapsed ($\triangle_t$) between certain points in a timeline. Such points can be the *begin* (x^-) and/or *end* (x^+) events of the continuous media involved (See Fig. 1). Only few works deal with the problem in an asynchronous manner (Grigoras et. al, 2003; Grigoras et. al, 2005; Yutaka et. al, 1999; Chang et. al, 2003; Kshemkalyani, 1996). They primarily take into account logical dependencies instead of temporal dependencies. One representative work is the model introduced in (Grigoras et. al, 2003; Grigoras et. al, 2005), which determines the possible relations of continuous media by identifying causal dependencies between the *begin* and *end* events. For example, in Fig. 1, Grigoras et al. establish the overlaps relation as ($v^- \rightarrow a^- \wedge a^- \rightarrow v^+ \wedge v^+ \rightarrow a^+$).

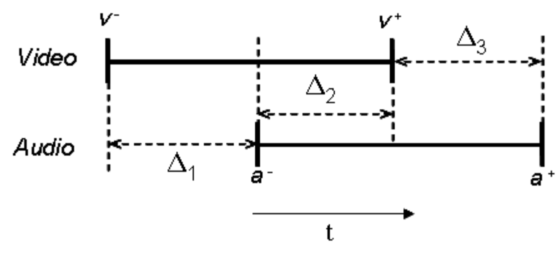

Figure 1: Example of a temporal scenario.

Neither approach taken by the works in the two general categories fulfills the requirements needed to solve the issue of preserving temporal relationships. This can be explained by several reasons. First, it is not easy to have a common reference in distributed systems since these involve the lack of a global

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time clock and shared memory. Second, solely considering logical dependencies among *begin* and *end* events may result in inaccurate executions. For example, a synchronization mechanism can ensure that the reproduction of events fulfills $v^- \rightarrow a^-$, but the model does not specify how much time must elapse between the reproduction of v^- and a^-.

In this paper we propose a solution belonging to the asynchronous category that attempts to resolve the problem related to possible imprecisions. To achieve this, we work with the continuous media at two abstract levels. At the higher level, the temporal duration is taken into account by representing the continuous media segments as intervals. At the lower level, we work with intervals, considering that an interval is composed of a set of sequentially-ordered messages. Taking into consideration these two abstract levels, our synchronization model translates temporal scenarios to be expressed as subintervals (segments) arranged according to their logical precedence dependencies. This translation results in the creation of what we call *logical mappings*.

The structure of this paper is as follows. We present in Section 2 the system model, the background and some required definitions. The Temporal Synchronization Model is presented in detail in Section 3. We introduce in Section 4 our Synchronization Mechanism. Finally, conclusions are provided in Section 5.

2 PRELIMINARIES

2.1 The System Model

Processes: The application under consideration is composed of a set of processes $P = \{i, j...\}$, organized into a group that communicates by reliable broadcast asynchronous messages. A process can only send one message at a time.

Messages: We consider a finite set of messages M, where each message $m \in M$ is identified by a tuple $m = (p, x)$, where $p \in P$ is the sender of m, denoted by $Src(m)$, and x is the local logical clock for messages of p when m is broadcasted. The set of destinations of a message m is always P.

Events: Let m be a message. We denote by $send(m)$ the emission event of m by $Src(m)$, and by $delivery(p, m)$ the delivery event of m to participant $p \in P$. The set of events associated to M is then the set $E = \{send(m) : m \in M\} \cup \{delivery(p, m) : m \in M \wedge p \in P\}$. The process $p(e)$ of an event $e \in E$ is defined by $p(send(m)) = Src(m)$ and $p(delivery(p, m)) = p$. The set of events of a process p is $E_p = \{e \in E : p(e) = p\}$.

Intervals: We consider a finite set I of intervals, where each interval $A \in I$ is a set of messages $A \subseteq M$ sent by a participant $p = Part(A)$, defined by the mapping $Part : I \rightarrow P$. Formally, we have $m \in A \Rightarrow Src(m) = Part(A)$. Due to the sequential order of $Part(A)$, we have for all $m, m' \in A, m \rightarrow m'$ or $m' \rightarrow m$. We denote by a^- and a^+ the endpoint messages of A, such that for all $m \in A : a^- \neq m$ and $a^+ \neq m \Rightarrow a^- \rightarrow m \rightarrow a^+$.

2.2 Background and Definitions

2.2.1 The Happened-Before Relation for Single Events

The happened-before relation, also known as the causal relation, was introduced in (Lamport, 1978). It is a strict partial order (*i.e.* irreflexive, asymmetric, and transitive) defined as follows:

Definition 1. The causal precedence relation, denoted by "$\rightarrow$", is the partial order generated by the following pair:

1. $e \rightarrow e'$ for all e, e' such that $p(e) = p(e')$ and e occurs before e' on $p(e)$
2. $send(m) \rightarrow delivery(k, m)$ for every message m and process k

We note that the complement to the causal precedence is the concurrent relation defined as $e \parallel e' \Rightarrow \neg(e \rightarrow e' \vee e' \rightarrow e)$. The precedence relation on messages denoted by $m \rightarrow m'$ is induced by the precedence relation on events, and is defined by $m \rightarrow m' \Rightarrow send(m) \rightarrow send(m')$.

A behavior or a set of behaviors satisfies *causal order delivery* if the diffusion of a message m causally precedes the diffusion of a message m', and the delivery of m causally precedes the delivery of m' for all participants that belong to P. Formally, we have:

Definition 2. Causal Order Delivery (broadcast case): If $send(m) \rightarrow send(m')$, then $\forall p \in P : delivery(p, m) \rightarrow delivery(p, m')$

2.2.2 The Partial Causal Relation

The Partial Causal Relation (PCR) was introduced in (Fanchon et. al, 2004) (Definition 3). It considers a subset $M' \subseteq M$ of messages. The PCR induced by M' considers the subset of events $E' \subseteq E$ that denote $E' = \{send(m), m \in M'\} \cup \{delivery(p, m), m \in M', p \in P\}$. For any identifier $p \in P$, we have $E_p^{'} = E' \cap E_p$. The partial precedence $\rightarrow_{M'} \subseteq E' \times E'$ induced by M' is the least partial order relation (transitive and acyclic) on E' and it is defined as follows:

Definition 3. The partial causal relation "$\rightarrow_{M'}$" is the least partial order relation satisfying the two following properties:

1. For each participant $p \in P$, the local restrictions of $\rightarrow_{M'}$ and $\rightarrow$ to the events of $E_p^{'}$ coincide: $\forall e, e' \in E_p^{'} : e \rightarrow e' \Leftrightarrow e \rightarrow_{M'} e'$.
2. For each message $m \in M'$ and $p \in P$, the emission of m precedes its delivery to p: $send(m) \rightarrow_{M'} delivery(p, m)$.

2.2.3 Happened-Before Relation for Intervals

In (Lamport, 1986) it was established that an interval A precedes or happens before another interval B if all elements that compose interval A causally precede all elements of interval B. This definition is used in the model presented in Section 3. However, it is well known that causal ordering implicates a computational high cost in terms of overhead, delay and processing time. For this reason, in order to reduce the cost, our mechanism presented in Section 4 uses the definition of the *happened-before* relation for intervals that was proposed in (Morales, 2005) (Definition 4) which is expressed only in terms of the interval endpoints. This definition says that if the elements of an interval are sequentially ordered, then ensuring partial causal order (Definition 3) on the interval endpoints is sufficient to ensure causal ordering at an interval level.

Definition 4. The relation "$\rightarrow_I$" on the set of intervals I of a system is accomplished if it satisfies the following two conditions:

1. $A \rightarrow_I B$ if $a^+ \rightarrow_{M'} b^-$
2. $A \rightarrow_I B$ if $\exists C | (a^+ \rightarrow_{M'} c^- \wedge c^+ \rightarrow_{M'} b^-)$

where a^+ and b^- are the right and left endpoints (messages) of A and B, respectively, c^- and c^+ are the endpoints of C, and $\rightarrow_{M'}$ is the partial causal order (Definition 3) induced on $M' \subseteq M$ where M', is the subset composed by the endpoint messages of the intervals in I. The second condition is the transitive property. Now, we present the simultaneous relation for intervals as follows:

Definition 5. Two intervals, A and B, are said to be simultaneous "$|||$" if the following condition is satisfied:

$A|||B \Rightarrow a^- \parallel b^- \wedge a^+ \parallel b^+$

Finally, we present the definition of causal delivery for intervals based on their endpoints as follows:

Definition 6. Causal Broadcast Delivery for Intervals

If $(a^+, b^-) \in A \times B, send(a^+) \rightarrow_{M'} send(b^-) \Rightarrow \forall p \in P, delivery(p, a^+) \rightarrow_{M'} delivery(p, b^-)$, then $\forall p \in P, delivery(p, A) \rightarrow_I delivery(p, B)$

2.3 Temporal Synchronization Model

In order to achieve the synchronization between continuous media in distributed systems, we propose to determine temporal relations based on the identification of logical precedence dependencies. To achieve this, we translate temporal scenarios to be expressed in terms of the precedence relation and the simultaneous relation; we call these translations *logical mappings*. More explicitly, in our work, a logical mapping decomposes a temporal scenario into data segments (events) that are arranged according to their possible precedence dependencies.

2.4 Logical Mappings

The process to create logical mappings (Table 1) involves taking every pair of intervals in the system that compose a temporal scenario, and translating each pair into four data segments, which are determined according to the possible precedence dependency of the discrete events that compose them. These data segments, according to our definition, become new intervals. The resulting intervals are only expressed in terms of the happened-before relation and the simultaneous relation[1].

Table 1: Logical Mapping.

$\forall(X,Y)$	$\in$	$I \times I$
$A(X,Y)$	$\leftarrow$	• $\{x \in X : x \rightarrow y^-\}$ if $x^- \rightarrow y^-$ or • $\emptyset$ otherwise
$B(X,Y)$	$\leftarrow$	• $\{y \in Y : x^+ \rightarrow y\}$ if $x^+ \rightarrow y^+$ or • $\{x \in X : y^+ \rightarrow x\}$ if $y^+ \rightarrow x^+$ or • $\emptyset$ otherwise
$C(X,Y)$	$\leftarrow$	$X - (A(X,Y) \cup B(X,Y))$
$D(X,Y)$	$\leftarrow$	$Y - B(X,Y)$
$W(X,Y)$	$\leftarrow$	$C|||D$
$S(X,Y)$	$\leftarrow$	$A \rightarrow_I W \rightarrow_I B$

In order to consider the seven basic relations and their inverses, and to maintain the model simplified, we first identify the X and Y intervals for each pair of intervals in the system. The X interval will be the interval with the first left endpoint, and the Y interval will be the remaining interval. This is done to ensure

[1]We consider in our work that an interval can be empty. In such case, the following properties apply:

- $\emptyset \rightarrow_I A \vee A \rightarrow_I \emptyset = A$
- $\emptyset|||A \vee A|||\emptyset = A$

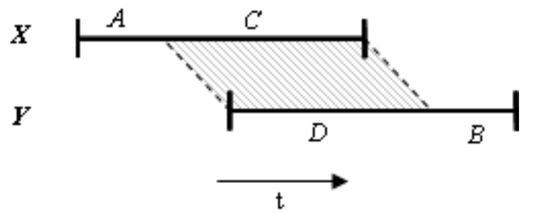


Figure 2: $X \, overlaps Y$ relation and its logical mapping $A \rightarrow_I (C|||D) \rightarrow_I B$.

that for every pair, $x^- \rightarrow y^-$ or $x^-||y^-$ at all times. Once the X and Y intervals are identified, the model segments each pair into four subintervals, A, B, C and D (see Table 1). We now proceed to construct the general causal structure $S = A \rightarrow_I W \rightarrow_I B$, where W determines if overlaps exist between the present pair. For example, for the overlaps relation defined in (Allen, 1983), the logical mapping is equal to $A \rightarrow_I (C|||D) \rightarrow_I B$ (See Fig. 2). Our model defines five possible logical mappings (Table 2, right column), which we call: *precedes, overlaps, ends, starts*, and *simultaneous*. These five logical mappings are sufficient to represent the thirteen relations established in (Allen, 1983). As shown in Table 2, we are now able to express every possible temporal relation by only considering the interval happened-before relation and the interval simultaneous relation.

2.5 Synchronization Mechanism

Our synchronization mechanism carries out two main functions that allow the continuous media to be presented according to the temporal model previously presented. The first function makes the translation of temporal relations (logical mappings), and the second function ensures the presentation of the intervals (data segments) according to the resultant logical mapping.

In order to carry out the temporal synchronization, our mechanism, which is based on the resultant logical mapping, determines if an interval must begin to be delivered or not according to whether it satisfies or not its causal dependency. For example, in Figure 2, interval A precedes interval D. Therefore, interval D will not begin to be delivered until all messages of A have been delivered. When the intervals are simultaneous in this case, C and D, the messages of C can be delivered in any order with respect to the messages of D.

General description. Internally, the mechanism uses two kinds of ordered messages: causal messages and FIFO messages. We have three different causal messages: *begin, end,* and *cut*. The *begin* and *end* messages are the left and right endpoints of the original intervals, and *cut* is a control message used by the mechanism to inform about an interval segmentation. FIFO messages $(fifo\_p)$ are used only inside an interval. We note that all causal and FIFO messages carry data of the continuous media involved. In order to ensure the causal order delivery at an interval level according to Definition 6, our algorithm uses vector clocks (Fidge, 1989) and the immediate dependency relation (IDR) (Pomares et. al, 2004). We use the IDR relation to determine the sufficient causal control information that must be attached per message. Next, we describe the main components of the mechanism.

2.6 Data Structures

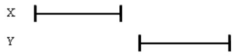
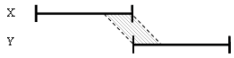
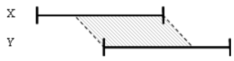
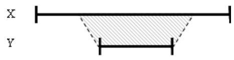
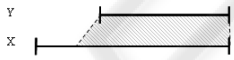
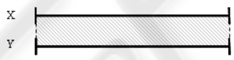
Local states. The state of a process p is defined by three data structures: $VT(p)$, $CI(p)$ and $last\_fifo(p)$.

- $VT(p)$ **is the vector time.** For each process p there is an element $VT(p)[j]$ where j is a process identifier. A process can only send one message at a time. The size of VT is equal to the number of processes in the group. The element $VT(p)[j]$ represents the greatest number of messages of the identifier j and "seen" in causal order by p. It is through the $VT(p)$ structure that we are able to guarantee the causal delivery at an interval level.
- $CI(p)$ **is the control information structure.** It is a set of entries $c_{k,t} = (k, t)$ where (k, t) is a message identifier (the message diffused by the process identifier k with the local message clock value t). Structure $CI(p)$ also contains information about the causal history of p.
- $last\_fifo(p)$ **is the fifo control information structure.** It is a structure composed by a set of entries (k, t), where (k, t) is a message identifier. The $last\_fifo$ structure has information about the last $(fifo\_p)$ messages received by p. These $(fifo\_p)$ messages represent potential causal messages.

Messages. The mechanism uses causal messages (*begin, end, cut*) and FIFO messages $(fifo\_p)$. A message m, in general, is composed of an identifier (k, t), an attached causal information $H(m)$, and continuous media data in the structure called $data$. For $fifo\_p$ messages, structure $H(m)$ is always $H(m) = \oslash$. Formally, a message m is a tuple $m = (k, t, TP, H(m), data)$, where:

- k is the identifier of sender $k = Src(m)$.
- $t = VT(p)[k]$ is the (local) clock value of p for the identifier k when a causal message m (*begin, end,*

Table 2: Allen's relations and their corresponding logical mappings.

Allen's Relations	**Endpoints**	**Interval Temporal Relation**	**Logical Mappings**
X before Y *Y after X*	$x^+ \rightarrow y^-$		***Precedes:*** $A \rightarrow_I B$
X meets Y *Y meet-by X*	$x^+ \Vert y^-$		
X overlaps Y *Y overlap-by X*	$x^- \rightarrow y^- \rightarrow x^+ \wedge$ $x^+ \rightarrow y^+$		***Overlaps:*** $A \rightarrow_I (C \vert\vert\vert D) \rightarrow_I B$
X includes Y *Y during X*	$x^- \rightarrow y^- \wedge$ $y^+ \rightarrow x^+$		
X starts Y *Y started-by X*	$x^- \parallel y^- \wedge$ $x^+ \rightarrow y^+$		***Starts:*** $(C \vert\vert\vert D) \rightarrow_I B$
X finishes Y *Y finished-by X*	$x^+ \parallel y^+ \wedge$ $x^- \rightarrow y^-$		***Ends:*** $A \rightarrow_I (C \vert\vert\vert D)$
X equals Y	$x^- \parallel y^- \wedge$ $x^+ \parallel y^+$		***Simultaneous:*** $C \vert\vert\vert D$

or cut) is sent. The value of t indicates the sequential number to which causal message m belongs.

- TP is the type of message ($begin, end, cut, fifo\_p$).
- $H(m)$ contains identifiers of messages (k, t) causally preceding causal message m, which denotes the *begin* and/or *end* of other intervals. The information in $H(m)$ ensures the causal delivery of message m. Structure $H(m)$ is built before a causal message is broadcasted, and then it is attached to the causal message.
- $data$ is the structure that carries the media data.

2.7 Example Scenario

Construction of logical mappings. We explain the creation of logical mappings in the example of the overlaps relation shown in Fig. 3. The referenced lines correspond to the code shown in the Table 3. In this example, segment A must first be determined. To achieve this, we map the left causal boundary a^- with the *begin* send event $send(\ x^- = x_1)$, and the right causal boundary with the send event $send(a^+ = x_k)$. The right endpoint a^+ is determined by the last $(fifo\_p)$ message received by participant j before the *begin* send event $send(y^-)$ (lines 16-20). Once we know the causal boundaries of A, we determine the set of messages that compose it ($A = \{x_1, x_2, ..., x_k\}$). After interval A is identified, we proceed to determine the causal boundaries of C and D. At this point, we can identify the left causal boundaries $c^- = x_{k+1}$ and $d^- = y_1$. However, it is only until the *end* send event of endpoint x^+ and its corresponding *delivery* event that we can identify the right endpoints of C and D. With the *end* send event $send(x^+ = x_n)$ we establish that $c^+ = x_n$, and consequently, $C = \{x_{k+1}, x_{k+2}, ..., x_n\}$. At the reception of x^+ by participant j, our algorithm sends a *cut* message (lines 49-51) which establishes the end of interval $D(d^+ = y_l)$ and the beginning of interval $B(cut = b^- = y_{l+1})$. As a result, we have $D = \{y_1, y_2, ..., y_l\}$. Finally, with the send event of y^+, we have $b^+ = y_m$, and consequently, $B = \{y_{l+1}, y_{l+2}, ..., y_m\}$.

In general, our mechanism considers three important rules to create logical mappings:

1. **When** $x^- \rightarrow y^-$**:** the right endpoint a^+ is determined by the last $(fifo\_p)$ message received by participant j before the send event of y^-, where $j = Part(Y)$.
2. **When** $x^+ \rightarrow y^+$**:** at the reception of x^+ by participant j, we generate on j a *cut* message (only if

Table 3: Specification of the synchronization mechanism.

Initially
1. $VT(p)[j] = 0, \forall j : 1, ..., n$
2. $CI(p) \leftarrow \oslash$
3. $last\_fifo(p) \leftarrow \oslash$
4. $Act = 0$
For each message m diffused by p with the process identifier i
5. $\mathbf{send}(Input : TP = \{begin \vert end \vert cut \vert fifo\_p\})$
6. $VT(p)[i] = VT(p)[i] + 1$
7. If not ($TP = fifo\_p$) then
8. If not ($TP = begin$) then /*Construction of the $H(m)$for end and cut messages*/
9. $H(m) \leftarrow CI(p)$
10. if ($TP = end$) then
11. $Act = 0$ /*Indicates that process p is inactive*/
12. endif
13. else /*Construction of the $H(m)$ for begin messages*/
14. $Act = 1$ /*Indicates that process p is sending an interval*/
15. $\forall(s, r) \in CI(p)$
16. if $\exists(x, l) \in last\_fifo(p) \mid s = x$ then /*Adding info about $fifo\_p$ messages to CI(p)*/
17. if not ($(s, r) = max\{(x, l), (s, r)\}$) then
18. $CI(p) \leftarrow CI(p) \cup (x, l)$
19. endif
20. endif
21. $H(m) \leftarrow CI(p)$
22. $last\_fifo(p) \leftarrow \oslash$
23. endif
24. $CI \leftarrow \oslash$ /*Erases the $CI(p)$ on each causal message sent*/
25. else */Construction of the $H(m)$ for $fifo\_p$ messages*/
26. $H(m) \leftarrow \oslash$
27. endif
28. $m = (i, t = VT(p)[i], TP, H(m), data)$
29. $sending(m)$
For each message received by p with process identifier j
30. $\mathbf{receive}(m)$ in p with $i \neq j$ and $m = (k, t, TP, H(m), data)$
31. If $t = VT(p)[k] + 1$ then /* FIFO delivery condition*/
32. If not ($TP = fifo\_p$) then
/*Causal delivery condition*/
33. If not $(t' \leq VT(p)[l]) \forall (l, t') \in H(m))$ then
34. *wait*()
35. else /*Causal delivery procedure*/
36. $delivery(m)$
37. $VT(p)[k] = VT(p)[k] + 1$

38.	If $\exists(s,r) \in CI(p) \mid k = s$ then
39.	$CI(p) \leftarrow CI(p) \setminus \{(s,r)\}$
40.	endif /*Updating $CI(p)$ with a more recent message*/
41.	$CI(p) \leftarrow CI(p) \cup \{(k,t)\}$
42.	$\forall(l,t') \in H(m)$ /*Clears $CI(p)$ and $last\_fifo(p)$ */
43.	If $\exists(s,r) \in CI(p) \mid l = s$ and $r \leq t'$ then
44.	$CI(p) \leftarrow CI(p) \setminus (s,r)$
45.	endif
46.	If $\exists(x,l) \in last\_fifo(p) \mid l = x$ and $l \leq t'$ then
47.	$last\_fifo(p) \leftarrow last\_fifo(p) \setminus (x,l)$
48.	endif
49.	If $Act = 1$ and not$(TP = cut)$ and not$(TP = begin)$ then
50.	$send(cut)$ /*Sending a cut message*/
51.	endif
52.	endif
53.	else /*FIFO delivery procedure*/
54.	$delivery(m)$
55.	$VT(p)[k] = VT(p)[k] + 1$
56.	If $\exists(x,l) \in last\_fifo(p) \mid k = x$ then
57.	$last\_fifo(p) \leftarrow last\_fifo(p) \setminus (x,l)$
58.	endif /*Updating $last\_fifo(p)$ with a more recent message*/
59.	$last\_fifo(p) \leftarrow last\_fifo(p) \cup (k,t)$
60.	endif
61.	else
62.	*wait*()
63.	endif

j is sending an interval), which determines the beginning of interval B ($cut = b^- = y_{l+1}$) and the end of interval $D(d^+ = y_l)$.

3. **When $y^+ \rightarrow x^+$:** at the reception of y^+ by participant $i = Part(X)$, we generate on i a *cut* message (only if i is sending an interval), which determines the beginning of interval B ($cut = b^- = x_{q+1}$) and the end of interval $C(c^+ = x_q)$.

Carrying out causal order delivery. The resultant logical mapping for the example scenario is $A \rightarrow_I (C|||D) \rightarrow_I B$. To ensure interval causal delivery in terms of their endpoints (Definition 6) we need to ensure that:

- *delivery*(a^+) $\rightarrow_{M'}$*delivery*(c^-),
- *delivery*(a^+) $\rightarrow_{M'}$*delivery*(d^-),
- *delivery*(c^+) $\rightarrow_{M'}$*delivery*(b^-) and
- *delivery*(d^+) $\rightarrow_{M'}$*delivery*(b^-)

Since $a^+ = x_k$, $c^- = x_{k+1}$, $d^+ = y_l$ and $b^- = y_{l+1}$, the procedure of *delivery*(a^+) $\rightarrow_{M'}$*delivery*(c^-) and *delivery*(d^+) $\rightarrow_{M'}$*delivery*(b^-) is accomplished by the FIFO property implemented by lines 6 and 31. The procedure of *delivery*(a^+) $\rightarrow_{M'}$*delivery*(d^-) is accomplished in the following way. Initially, message $a^+ = x_k$ is sent as $fifo\_p$. To consider it as a causal message, process j includes information concerning x_k in its causal history (lines 16-20), and attaches this information to structure $H(m)$ of the message $d^- = y_1$ before its send event (line 21).

The causal delivery condition (line 33) ensures that the beginning of interval D (d^-) will be delivered only after the delivery of x_k, and the FIFO condition (line 21) ensures that x_k will be delivered only after the delivery of all messages $x_h \in A \subseteq X$, such that $h < k$. For the requirement of *delivery*(c^+) $\rightarrow_{M'}$*delivery*(b^-), message $b^- = y_{l+1}$ has attached information on its structure $H(m)$ about the message $c^+ = x_n$ (lines 15-21). The causal delivery condition (line 33) ensures that the beginning of interval B (b^-) will be delivered only after the delivery of x_n, and the FIFO condition (line 21) ensures that x_n will be delivered only after the delivery of all messages $x_q \in C \subseteq X$, such that $q < n$.

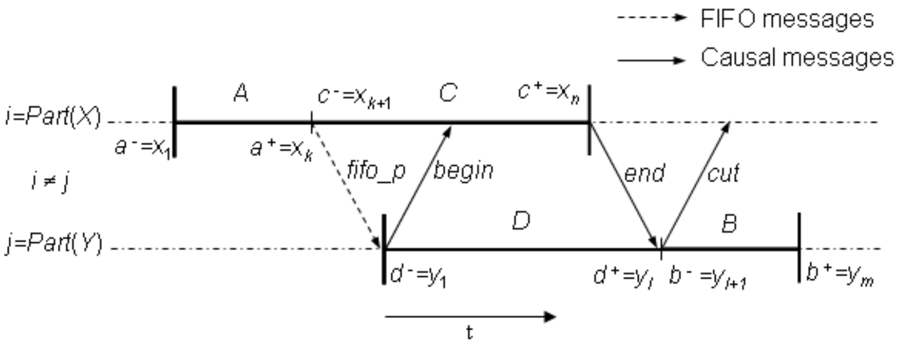


Figure 3: Construction of the logical mapping ($A \rightarrow_I (C|||D) \rightarrow_I B$) for the overlaps relation.

3 CONCLUSIONS

An innovative temporal synchronization mechanism has been presented. The mechanism addresses in an asynchronous manner the problem of preserving temporal relations for real-time distributed media streams. The core of our mechanism is the delivery of streams according to the resultant logical mapping which is based on the causal dependencies of the continuous media involved. The mechanism uses the partial causal relation and the immediate dependency relation to reduce the causal overhead. Further work is needed to enhance our mechanism so that it can support real network conditions (loss of messages, lifetime of messages, etc.). Our attention is focused in this direction, and we expect to publish some interesting contributions shortly.

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