

A Temporal Synchronization Model for Heterogeneous Data in Distributed Systems

Jorge Estudillo Ramirez and Saul E. Pomares Hernandez

Abstract—Multimedia distributed systems deal with heterogeneous data, such as texts, images, graphics, video and audio. The specification of temporal relations among different data types and distributed sources is an open research area. This paper proposes a fully distributed synchronization model to be used in multimedia systems. One original aspect of the model is that it avoids the use of a common reference (e.g. wall clock and shared memory). To achieve this, all possible multimedia temporal relations are specified according to their causal dependencies.

Keywords—Multimedia, Distributed Systems, Partial Ordering, Temporal Synchronization

I. INTRODUCTION

MULTIMEDIA systems deal with heterogeneous data such as texts, graphics, images, audio, video and animations. Multimedia data is generally grouped into two types: *continuous media* (e.g. audio and video) and *discrete media* (e.g. texts, data and images)[1]. The main difference between these two types is that while continuous media events are considered to be executed during a period of time, discrete media events are considered to be executed at specific timeless points (See Fig. 1). One open research area in multimedia distributed systems involves intermedia synchronization, which concerns the preservation of temporal dependencies among the media data from the time of generation to the time of presentation. Several works attempt to give a possible solution [1], [2], [3], [4], [5]; however, these works are far from resolving the problem. In this paper we propose an extension to the synchronization model presented by Morales et al. [2]. Morales's model specifies all temporal relations for continuous media (interval-interval relations) based on the possible causal dependencies of the media data involved. The extension that we propose considers the integration of continuous and discrete media, which includes point-intervals relations and point-to-point relations. With this extension we are able to specify all possible temporal relations in multimedia scenarios.

This paper is structured as follows. Section 2 presents the most relevant related work. Next, in Section 3, the system model is described and the background information is provided. In Section 4, the temporal model concerning discrete and continuous media is presented. Conclusions are given in Section 5.

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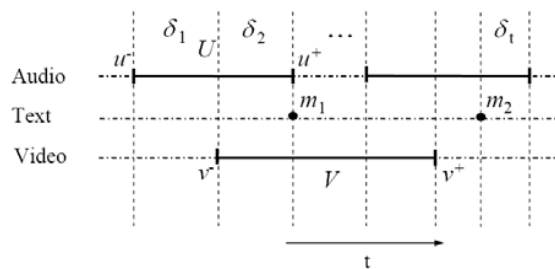


Fig. 1. A multimedia scenario example

II. RELATED WORK

Many works related to multimedia synchronization exist. Most of them implement intermedia synchronization by considering point-to-point communication, and they are primarily based on the identification of time constraints by using a common reference (clock, memory, mixer, etc) [1], [6], [7]. These works usually try to answer the synchronization problem by measuring in a timeline the period of physical or virtual time elapsed (δ_i) between certain points. Such points can be the *begin* (x^-), *end* (x^+) and/or discrete events (m_1) of the media involved (Fig. 1).

Few works address intermedia synchronization without the use of a global reference, which is desirable when the media data have different sources [8]. These last works are primarily based on the identification of logical dependencies [2], [3], [4]. In this paper, we only present the work related to the last category, with which we are concerned.

One interesting work is the model introduced by Shimamura et al. [3], which establishes six logical precedence relations at an object level (*top*, *tail*, *full*, *partial*, *inclusive* and *exclusive*). These relations are specified based on the causal dependencies of the *begin* (x^-) and *end* (x^+) points of the objects. The objects are represented by intervals composed by messages. To obtain a fine level synchronization, Shimamura introduces an interval segmentation mechanism that divides the objects into predetermined fixed length segments. This mechanism uses two logical relations: the *precedes* relation and the *concurrent* relation. The *precedes* relation of Shimamura is defined as:

$$A \rightarrow B \text{ if } a^+ \rightarrow b^-$$

while the *concurrent* relation is defined as:

$$A \parallel B \text{ if } \neg(a^+ \rightarrow b^-) \wedge \neg(b^+ \rightarrow a^-)$$

We note that this mechanism can be inaccurate since it considers that a pair of segments (intervals) can only be either *causally* or *concurrently* related, which as Allen shows

[9] is not enough to consider all possible temporal interval relations. Allen identifies seven possible basic relations (*before*, *meets*, *overlaps*, *starts*, *finishes*, *includes*, *equals*). Shimamura's *concurrent* relation excludes the *before* relation but includes the remaining relations established by Allen; in other words, the remaining six relations are considered by Shimamura as "concurrent" without making any distinction between them (see Table I). A pair of concurrently related segments (intervals) implies that no order can be established between the messages that compose them.

Plesca et al. [4] have considered a practical approach for intermedia synchronization by using causal dependencies. Plesca's work uses causal messages as synchronization points to satisfy temporal dependencies among media streams. This work, in a heuristic manner, introduces causal synchronization points and shows that these points can be useful, but it does not resolve the problems of when nor of how many causal messages must be used.

A recent approach that attempts to avoid inaccurate executions is presented by Morales et al. [2]. This work introduces the concept of *logical mappings*. A logical mapping decomposes each possible interval-interval temporal relation into four possible segments arranged according to their causal dependencies. The resulting intervals (segments) that compose a logical mapping are expressed only in terms of the *happened-before* relation and the *simultaneous* relation that Morales defines at an interval level (Definitions 3 and 4). To be more explicit, a logical mapping specifies a temporal relation by exactly determining the segments that happened before or that overlap in time (see Table I). We emphasize that the works done by Shimamura, Plezca and Morales only address the synchronization problem for continuous media (i.e. interval-interval relations).

III. PRELIMINARIES

A. The System Model

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

Packets: We consider a finite set of packets M , where each packet $m \in M$ is identified by a tuple $m = (p, x)$, where $p \in P$ is the sender of m , and x is the local logical clock for packets of p , when m is broadcasted. The set of destinations of a packet m is always P . We define that for all $m, m' \in P$ implies $m \rightarrow m'$ or $m' \rightarrow m$.

Events: Let m be a packet. We denote by $send(m)$ the emission event and by $delivery(p, m)$ the delivery event of m to participant $p \in P$. The set of events associated to M is 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 $p(send(m)) = p$ 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 packets $A \subseteq M$ sent by participant $p = Part(A)$, defined by the mapping $Part : I \rightarrow P$. We denote by a^- and a^+ the endpoint packets of A , and due to

the sequential order of $Part(A)$, we have that for all $m \in A : a^- \neq m$ and $a^+ \neq m$ implies that $a^- \rightarrow m \rightarrow a^+$. We note that when $|A| = 1$, we have that $a^- = a^+$; in this case, a^- and a^+ are denoted indistinctly by a .

B. Background and Definitions

Happened-Before Relation for Discrete Media. The Happened-Before relation is a strict partial order [8] (i.e. irreflexive, asymmetric and transitive) denoted by $e \rightarrow e'$ (i.e. e causally precedes e') defined as follows:

Definition 1: The causal relation " \rightarrow " is the least partial order relation on E satisfying the two following properties:

- 1) For each participant p , the set of events E_p involving p is totally ordered: $e, e' \in E_p \Rightarrow e \rightarrow e' \vee e' \rightarrow e$
- 2) For each message m and destination $p \in P$ of m , the emission of m precedes its delivery; i.e. $send(m) \rightarrow delivery(p, m)$

By using " \rightarrow ", Lamport defines that two events are concurrent as follows:

$$e \parallel e' \text{ if } \neg(e \rightarrow e' \vee e' \rightarrow e)$$

Partial Causal Relation (PCR). The PCR relation was introduced by Pomares et al. [10] (Definition 2). It considers a subset $M' \subseteq M$ of packets. The PCR induced by M' takes into account the subset of events $E' \subseteq E$ that refer to *send* or *delivery* events of the packets belonging to M' . In our work, the PCR relation is a weak partial order (i.e. *reflexive*, *asymmetric*, and *transitive*) since when $|A| = 1$, we have that $a^- = a^+ = a$; and in this case, we consider $a \rightarrow a$.

Definition 2: 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 packet $m \in M'$ and $j \in P$, the emission of m precedes its delivery to $j : j \in P \Rightarrow send(m) \rightarrow_{M'} delivery(j, m)$

Happened-Before Relation for Intervals. Lamport [11] establishes that an interval A 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 4. However, the causal interval relation can be expressed only in terms of the endpoints [2] as follows:

Definition 3: The relation \rightarrow_I and \rightarrow is accomplished if the following two conditions are satisfied:

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

where a^+ and b^- are the final and initial send events (or packets) of A and B , respectively, c^- and c^+ are the endpoints of C , and $\rightarrow_{M'}$ is the partial causal order (Definition 2) induced on $M' \subseteq M$, where M' , in this case, is the subset composed by the endpoint packets of the intervals in I .

Finally, we present the simultaneous relation for intervals, defined as follows:

Definition 4: Two intervals, A and B , are said to be simultaneous " \parallel " if the following condition is satisfied:

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

TABLE I
RELATED WORKS COMPARED WITH ALLEN'S ALGEBRA

Scenario Example	Allen's Relations	Morales's Approach at Segment Level	Shimamura's relations at Segment Level
	$X \text{ before } Y$	<i>precedes:</i> $A \rightarrow_I B$	$X \text{ precedes } Y$
	$X \text{ equals } Y$	<i>simultaneous:</i> $(C \parallel D)$	$X \text{ concurrent } Y$ $(X \parallel Y)$
	$X \text{ meets } Y$	<i>overlaps:</i> $A \rightarrow_I (C \parallel D) \rightarrow_I B$	
	$X \text{ overlaps } Y$		
	$X \text{ during } Y$	<i>starts:</i> $(C \parallel D) \rightarrow_I B$	
	$X \text{ starts } Y$		
	$X \text{ finishes } Y$		

The definition above means that one interval A can take place at the "same time" as another interval B .

IV. TEMPORAL SYNCHRONIZATION MODEL

We work at two abstract levels to achieve the synchronization between the three kinds of relations: point-point, point-interval and interval-interval. At the higher level, the multimedia data (discrete and continuous) is represented as intervals. At the lower level, we consider that an interval is a set of finite sequential elements (packets). We note that for discrete media, an interval is composed by a single element. Our model translates temporal multimedia scenarios (composing them by a set of intervals) to be expressed in terms of their precedence or simultaneous relations (Definitions 3 and 4). We call this translation *logical mapping* (See Table II).

The logical mapping translation (Table II) involves every pair of intervals of a temporal relation. Each interval is labeled as X or Y such that for every pair, $x^- \rightarrow y^-$ or $x^- \parallel y^-$. Once the X and Y intervals are identified, they

are segmented into four subintervals¹: $A(X, Y)$, $C(X, Y)$, $D(X, Y)$, and $B(X, Y)$. These data segments, considering our definition, become new intervals². Finally, we proceed to construct the general causal structure $S(X, Y) = A(X, Y) \rightarrow_I W(X, Y) \rightarrow_I B(X, Y)$, where $W(X, Y)$ determines if overlaps exist between the present pair. We note that the data segments are constructed based on the causal-effect relation of the endpoints.

For clarity, we present the logical mapping model into two parts. In the first part, we present the logical mapping for the possible point-point relations (See Table III). The second part shows how the process is carried out for the point-interval relations (See Table IV). The interval-interval case was explored in [2].

A. Logical Mappings for Discrete Media

Our model determines logical mappings to represent all possible point-point temporal relations identified by Vilain

¹We consider in our model that an interval can be empty. In such case, the following properties apply:
 $\emptyset \rightarrow_I A \vee A \rightarrow_I \emptyset = A$ and $\emptyset \parallel A \vee A \parallel \emptyset = A$

²Henceforth, we can refer to them only as A , C , D , and B when there is no ambiguity in the context

TABLE II
LOGICAL MAPPING PROCEDURE

$\forall(X, Y)$	\in	$I \times I$
$A(X, Y)$	\leftarrow	<ul style="list-style-type: none"> • $\{x \in X : x \rightarrow y^-\}$ if $x^- \rightarrow y^-$ or otherwise • \emptyset
$B(X, Y)$	\leftarrow	<ul style="list-style-type: none"> • $\{y \in Y : x^+ \rightarrow y\}$ if $x^+ \rightarrow y^+$ or • $\{x \in X : y^+ \rightarrow x\}$ if $y^+ \rightarrow x^+$ or otherwise • \emptyset
$C(X, Y)$	\leftarrow	$X - (A(X, Y) \cup B(X, Y))$
$D(X, Y)$	\leftarrow	$Y - B(X, Y)$
$W(X, Y)$	\equiv	$C \parallel D$
$S(X, Y)$	\equiv	$A \rightarrow_I W \rightarrow_I B$

[12]. Vilain establishes three basic relations based on a global reference, which are *before* ($<$), *simultaneous* ($=$) and *after* ($>$) (See Table III, left column). After applying our model (shown in Table II) to each possible temporal relation, we identify two possible logical mappings, which are *precedes* and *simultaneous* (See Table III, right column). When $x < y$ (*before* relation), we have $X = \{x\}$ and $Y = \{y\}$. By applying the model, we obtain the logical mapping $A \rightarrow_I B$.

TABLE III
VILAIN'S POINT-POINT RELATIONS AND THEIR LOGICAL MAPPING

Basic Point Relations	Logical Mapping	Logical Mapping Expressed on Endpoints
$x < y$	<i>precedes:</i> $A \rightarrow_I B$	$a \rightarrow b$
$y > x$		
$x = y$	<i>simultaneous:</i> $C \parallel D$	$c \parallel d$

B. Logical Mapping for Discrete and Continuous Media

Vilain's point-interval algebra [12] establishes five basic temporal relations based on a global reference (See Table IV, left column). We use Vilain's point-interval algebra to show that we determine a logical mapping to express every possible point-interval temporal relation. We note that our model considers an additional temporal relation called the *simultaneous* relation. This relation is not considered by Vilain because a single discrete element (a point) in his model cannot occur with more than one element of an interval at the same time (See Table IV, *y during X* point-interval relation).

By applying the model shown in Table II, we identify five possible logical mappings (*precedes*, *overlaps*, *ends*, *starts*, and *simultaneous*). We can see in Table IV that these logical mappings are sufficient to represent all possible point-interval temporal relations.

C. Scenario Example

In order to explain how the logical mapping is performed, we take the pair $V, \{m_1\}$ depicted in Fig. 2. The process of creating a logical mapping in our work is made by identifying the causal boundaries of the concerned intervals from left to right as the time elapses and the events occur.

In this example (See Figure 2), we first identify $X = V$ and $Y = \{m_1\}$ since $x^- \rightarrow y$. Then, we proceed to determine segment $A(V, m_1)$. The segment $A(V, m_1)$ will be constructed,

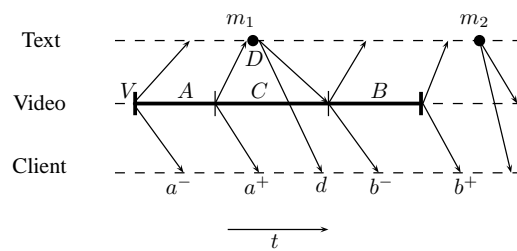


Fig. 2. Temporal Scenario example

according to Table II, for each element $x \in X$ such that $delivery(Part(Y), x) \rightarrow send(y)$. After interval segment $A(V, m_1)$ is identified, we proceed to identify the elements of the segments $C(V, m_1)$ and $D(V, m_1)$. In this case, since $y \rightarrow x^+$, segment $C(V, m_1)$ will be composed by each element $x \in X$ such that $send(x) \rightarrow delivery(Part(X), y^+)$ minus the elements of segment $A(V, m_1)$. Now, since $\neg(x^+ \rightarrow y^+)$ we have that $D(X, Y) = Y = \{m_1\}$. Finally, we establish the segment $B(V, m_1)$ as equal to $X - \{A(V, m_1) \cup C(V, m_1)\}$, since $y \rightarrow x^+$.

Interpreting the synchronization specification $S(V, m_1) = A(V, m_1) \rightarrow_I (C(V, m_1) \parallel D(V, m_1)) \rightarrow_I B(V, m_1)$ for the pair $V, \{m_1\}$ (see Fig. 2) means the following: Interval $A(V, m_1)$ identifies the subset of messages $v \in V$ that causally precede the sending of discrete media m_1 and that should be reproduced before $D(V, m_1) = \{m_1\}$. Interval $C(V, m_1)$ identifies the messages that are concurrent with $D(V, m_1)$ and that can be reproduced in any order with respect to $D(V, m_1)$. Finally, interval $B(V, m_1)$ identifies the messages that should be executed after $D(V, m_1)$. In terms of physical time and their endpoints, the period of time between the execution of $a^+ \in A(V, m_1)$ and $b^- \in B(V, m_1)$ establishes the valid period of time for when the discrete media $d \in D(V, m_1)$ should be executed at any reception process (Client).

According to Table III and Table IV, and the work done by Morales et al. [2], we are now able to work indistinctly with the three kinds of temporal relations (point-point, point-interval, and interval-interval) based on causal dependencies. We remark that this capacity is the core of our work.

V. CONCLUSIONS

We have presented a distributed temporal synchronization model that considers continuous media and discrete media. The core of the synchronization model is the construction of logical mappings that clearly specify any kind of temporal relation (interval-interval, point-interval, and point-point). The temporal synchronization model presented avoids the use of global references by identifying the possible causal dependencies of the media involved. At this time, we are working on the construction of a temporal synchronization mechanism based on the proposed model, and we expect to have some interesting results shortly.

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TABLE IV
VILAIN'S POINT-INTERVAL RELATIONS AND THEIR LOGICAL MAPPING

Vilain's Relations	Logical Mapping	Scenario Example	Logical Mapping Expressed on Endpoints
U before v	precedes: $A \rightarrow_I B$		$a^+ \rightarrow b$
v after U			
U starts v	starts: $(C \parallel\parallel D) \rightarrow_I B$		$c^- \parallel d, c^+ \rightarrow b^-$ $d \rightarrow b^-$
U finishes v	ends: $A \rightarrow_I (C \parallel\parallel D)$		$a^+ \rightarrow c^-, a^+ \rightarrow d$ $c^- \parallel d$
v during U	overlaps: $A \rightarrow_I (C \parallel\parallel D) \rightarrow_I B$		$a^+ \rightarrow c^-, a^+ \rightarrow d$ $c^- \parallel d, c^+ \parallel d$ $c^+ \rightarrow b^-, d \rightarrow b^-$
Not defined in Vilain's relations U simultaneous v	simultaneous: $C \parallel\parallel D$		$c^- \parallel d, c^+ \parallel d$

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