Total Order Broadcast and Multicast Algorithms: Taxonomy and Survey

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Total order broadcast and multicast (also called atomic broadcast/multicast) present an important problem in distributed systems, especially with respect to fault-tolerance. In short, the primitive ensures that messages sent to a set of processes are, in turn, delivered by all those processes in the same total order.

Categories and Subject Descriptors: C.2.4 [**Computer-Communication Networks**]: Distributed Systems; C.2.2 [**Computer-Communication Networks**]: Network Protocols—*Applications; Protocol architecture*; D.4.4 [**Operating Systems**]: Communications Management—*Message sending; Network communication*; D.4.5 [**Operating Systems**]: Reliability—*Fault-tolerance*; H.2.4 [**Database Management**]: Systems—*Distributed databases*; H.3.4 [**Information Storage and Retrieval**]: Systems and Software—*Distributed systems*

General Terms: Algorithms, Reliability, Design

Additional Key Words and Phrases: Distributed systems, distributed algorithms, group communication, fault-tolerance, agreement problems, message passing, total ordering, global ordering, atomic multicast, atomic broadcast, classification, taxonomy, survey

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Part of this research was conducted for the program "Fostering Talent in Emergent Research Fields" in Special Coordination Funds for Promoting Science and Technology by the Japan Ministry of Education, Culture, Sports, Science and Technology. This work was initiated during Xavier Défago's Ph.D. research at the Swiss Federal Institute of Technology in Lausanne [Défago 2000]. Péter Urbán was supported by the Japan Society for the Promotion of Science, a Grant-in-Aid for JSPS Fellows from the Japanese Ministry of Education, Culture, Sports, Science and Technology, the Swiss National Science Foundations, and the CSEM Swiss Center for Electronics and Microtechnology, Inc., Neuchâtel.

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The problem has inspired an abundance of literature, with a plethora of proposed algorithms. This article proposes a classification of total order broadcast and multicast algorithms based on their ordering mechanisms, and addresses a number of other important issues. The article surveys about sixty algorithms, thus providing by far the most extensive study of the problem so far. The article discusses algorithms for both the synchronous and the asynchronous system models, and studies the respective properties and behavior of the different algorithms.

1. INTRODUCTION

Distributed systems and applications are notoriously difficult to build. This is mostly due to the unavoidable concurrency in such systems, combined with the difficulty of providing a global control. This difficulty is greatly reduced by relying on group communication primitives that provide higher guarantees than standard point-to-point communication. One such primitive is called total order[1] broadcast.[2] Informally, the primitive ensures that messages sent to a set of processes are delivered by all those processes in the same order. Total order broadcast is an important primitive that plays a central role, for instance, when implementing the state machine approach (also called active replication) [Lamport 1978a; Schneider 1990; Poledna 1994]. It also has other applications, such as clock synchronization [Rodrigues et al. 1993], computer supported cooperative writing, distributed shared memory, and distributed mutual exclusion [Lamport 1978b]. More recently, it was also shown that an adequate use of total order broadcast can significantly improve the performance of replicated databases [Agrawal et al. 1997; Pedone et al. 1998; Kemme et al. 2003].

Literature on total order broadcast. There exists a considerable amount of literature on total order broadcast, and many algorithms, following various approaches, have been proposed to solve this problem. It is, however, difficult to compare them as they often differ with respect to their actual properties, assumptions, objectives, or other important aspects. It is hence difficult to know which solution is best suited to a given application context. When confronted with new requirements, the absence of a roadmap to the problem of total order broadcast can lead engineers and researchers to either develop new algorithms rather than adapt existing solutions (thus reinventing the wheel), or use a solution poorly suited to the application needs. An important step to improve the present situation is to provide a classification of existing algorithms.

Related work. Previous attempts have been made at classifying and comparing total order broadcast algorithms [Anceaume 1993b; Anceaume and Minet 1992; Cristian et al. 1994; Friedman and van Renesse 1997; Mayer 1992]. However, none is based on a comprehensive survey of existing algorithms, and hence they all lack generality.

The most complete comparison so far was done by Anceaume and Minet [1992] (an extended version was later published in French by Anceaume [1993b]), who take an interesting approach based on the *properties* of the algorithms. Their paper raises some fundamental questions that inspired a part of our work. It is, however, a little outdated now. In addition, the authors only study seven different algorithms, which are not truly representative; for instance, none is based on a communication history approach (one of the five classes of algorithms; details in Section 4.4).

[1]Total order broadcast is also known as atomic broadcast. Both terminologies are currently in use. There is a slight controversy with respect to using one over the other. We opt for the former, that is, "total order broadcast," because the latter is somewhat misleading. Indeed, atomicity suggests a property related to agreement rather than to total order (defined in Sect. 2), and the ambiguity has already been a source of misunderstandings. In contrast, "total order broadcast" unambiguously refers to the property of total order.

[2]Total order *multicast* is sometimes used instead of total order *broadcast*. The distinction between the two primitives is explained later in the article (Section 3). When the distinction is not important, we use the term total order *broadcast*.

Cristian et al. [1994] take a different approach, focusing on the implementation of the algorithms, rather than their properties. They study four different algorithms, and compare them using discrete event simulation. They find interesting results regarding the respective performance of different implementation strategies. Nevertheless, they fail to discuss the respective properties of the different algorithms. Besides, as they compare only four algorithms, this work is less general than Anceaume's [1993b].

Friedman and van Renesse [1997] study the impact of packing messages on the performance of algorithms. To this purpose, they study six algorithms, including those studied by Cristian et al. [1994]. They measure the actual performance of the algorithms and confirm the observations made by Cristian et al. [1994]. They show that packing several protocol messages into a single physical message indeed provides an effective way to improve the performance of algorithms. The comparison also lacks generality, but this is quite understandable as this is not the main concern of their paper.

Mayer [1992] defines a framework in which total order broadcast algorithms can be compared from a performance point of view. The definition of such a framework is an important step toward an extensive and meaningful comparison of algorithms. However, the paper does not actually compare the numerous existing algorithms.

Contributions. In this article, we propose a classification of total order broadcast algorithms based on the mechanism used to order messages. The reason for this choice is that the ordering mechanism is the characteristic with the strongest influence on the communication pattern of the algorithm: two algorithms of the same class are likely to exhibit similar behaviors. We define five classes of ordering mechanisms: *communication history*, *privilege-based*, *moving sequencer*, *fixed sequencer*, and *destinations agreement*.

In this article, we also provide a vast survey of about sixty published total order broadcast algorithms. Wherever possible, we mention the properties and the assumptions of each algorithm. This is, however, not always possible because the information available in the papers is often not sufficient to accurately characterize the behavior of the algorithm (e.g., in the face of a failure).

Structure. The article is logically organized into four main parts: specification, ordering mechanisms and taxonomy, fault-tolerance, and survey. More precisely, the article is structured as follows. Section 2 presents the specification of the total order broadcast problem (also known as atomic broadcast). Section 3 extends the specification by considering the characteristics of destination groups (e.g., single versus multiple groups). In Section 4, we define five classes of total order broadcast algorithms, according to the way messages are ordered: *communication history*, *privilege-based*, *moving sequencer*, *fixed sequencer*, and *destinations agreement*. Section 5 discusses system model issues in relation to failures. Section 6 presents the main mechanisms on which total order broadcast algorithms rely to ensure fault-tolerance. Section 7 gives a broad survey of total order broadcast algorithms found in the literature. Algorithms are grouped along their respective classes, and we discuss their principal characteristics. Section 8 discusses some other issues of interest that are related to total order broadcast. Finally, Section 9 concludes the article.

2. SPECIFICATION OF TOTAL ORDER BROADCAST

In this section, we give the formal specification of the total order broadcast problem. As there are many variants of the problem, we present here the simplest specification, and discuss other variants in Section 3.

2.1. Notation

Table I summarizes some of the notations used throughout the article. $\mathcal{M}$ is the set containing all possible valid messages. Π denotes the set of all processes in the system. Given some arbitrary

Table I. Notation

$\mathcal{M}$	set of all valid messages.
Π	set of all processes in the system.
sender(m)	sender of message m.
Dest(m)	set of destination processes for message m.
Π_{sender}	set of all sending processes in the system.
Π_{dest}	set of all destination processes in the system.

message m, $sender(m)$ designates the process in Π from which m originates, and $Dest(m)$ denotes the set of all destination processes for m.

In addition, Π_{sender} is the set of all processes in Π that can potentially send some valid message.

$$\Pi_{sender} = \{p \mid p \text{ can send some message } m \in \mathcal{M}\}. \quad (1)$$

Likewise, Π_{dest} is the set of all potential destinations of valid messages.

$$\Pi_{dest} \stackrel{\text{def}}{=} \bigcup_{m \in \mathcal{M}} Dest(m). \quad (2)$$

2.2. Process Failures

The specification of total order broadcast requires the definition of the notion of a *correct* process. The following set of process failure classes are commonly considered:

—*Crash failures.* When a process crashes, it ceases functioning forever. This means that it stops performing any activity including sending, transmitting, or receiving any message.

—*Omission failures.* When a process fails by omission, it omits performing some actions, such as sending or receiving a message.

—*Timing failures.* A timing failure occurs when a process violates some of the timing assumptions of the system model (details in Section 5.1). Obviously, this type of failures does not exist in asynchronous system models, because of the absence of timing assumptions in such systems.

—*Byzantine failures.* Byzantine failures are the most general type of failures. A Byzantine component is allowed any arbitrary behavior. For instance, a faulty process may change the content of messages, duplicate messages, send unsolicited messages, or even maliciously try to break down the whole system.

A *correct* process is defined as a process that never expresses any of the faulty behaviors mentioned above.

2.3. Basic Specification of Total Order Broadcast

We can now give the simplest specification of total order broadcast. Formally, the problem is defined in terms of two primitives, which are called *TO-broadcast*(m) and *TO-deliver*(m), where $m \in \mathcal{M}$ is some message. When a process p executes *TO-broadcast*(m) (respectively *TO-deliver*(m)), we may say that p TO-broadcasts m (respectively TO-delivers m). We assume that every message m can be uniquely identified, and carries the identity of its sender, denoted by $sender(m)$. In addition, we assume that, for any given message m, and any run, *TO-broadcast*(m) is executed at most once. In this context, total order broadcast is defined by the following properties [Hadzilacos and Toueg 1994; Chandra and Toueg 1996]:

(VALIDITY) If a correct process TO-broadcasts a message m, then it eventually TO-delivers m.

(UNIFORM AGREEMENT) If a process TO-delivers a message m, then all correct processes eventually TO-deliver m.

(UNIFORM INTEGRITY) For any message m, every process TO-delivers m at most once, and only if m was previously TO-broadcast by $sender(m)$.

(UNIFORM TOTAL ORDER) If processes p and q both TO-deliver messages m and m', then p TO-delivers m before m', if and only if q TO-delivers m before m'.

A broadcast primitive that satisfies all these properties except Uniform Total Order (i.e., that provides no ordering guarantee) is called a *reliable broadcast*.

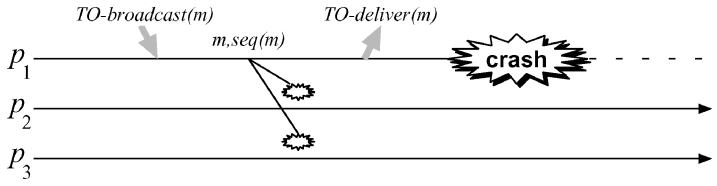


Fig. 1. Violation of Uniform Agreement (example).

Validity and Uniform Agreement are liveness properties. Roughly speaking, this means that, at any point in time, no matter what has happened up to that point, it is still possible for the property to eventually hold [Charron-Bost et al. 2000]. Uniform Integrity and Uniform Total Order are safety properties. This means that, if, at some point in time, the property does not hold, no matter what happens later, the property cannot eventually hold.

2.4. Nonuniform Properties

In the above definition of total order broadcast, the properties of Agreement and Total Order are *uniform*. This means that these properties do not only apply to correct processes, but also to faulty ones. For instance, with Uniform Total Order, a process is not allowed to deliver any message out of order, even if it is faulty. Conversely, (nonuniform) Total Order applies only to correct processes, and hence does not put any restriction on the behavior of faulty processes.

Uniform properties are strong guarantees that might make life easier for application developers. Not all applications need uniformity, however, and enforcing uniformity often has a cost. For this reason, it is also important to consider weaker problems specified using nonuniform properties, though nonuniform properties may lead to inconsistencies at the application level. However, an application might protect itself from nonuniformity by voting (e.g., given an application that collects replies from the destinations of a total order broadcast, the application may vote on the replies received, and consider a reply to be effective only after receiving the same reply from a majority). Nonuniform Agreement and Total Order are specified as follows:

(AGREEMENT) If a ***correct*** process TO-delivers a message m, then all correct processes eventually TO-deliver m.

(TOTAL ORDER) If two ***correct*** processes p and q both TO-deliver messages m and m', then p TO-delivers m before m', if and only if q TO-delivers m before m'.

The combinations of uniform and nonuniform properties define four different specifications to the problem of fault-tolerant total order broadcast. These definitions constitute a hierarchy of problems, as discussed extensively by Wilhelm and Schiper [1995]. However, for simplicity, we say that a total order broadcast algorithm is uniform when it satisfies both Uniform Agreement and Uniform Total Order, and we say that an algorithm is nonuniform when it enforces neither (i.e., only their nonuniform counterparts). We give no special name to the two hybrid definitions.

Figure 1 illustrates a violation of the Uniform Agreement property with a simple example. In this example, the sequencer p_1 sends a message m, using total order broadcast. It first assigns a sequence number to m, then sends m to all processes, and finally, delivers m. Process p_1 crashes shortly afterwards, and no other process receives m (due to message loss). As a result, no correct process (e.g., p_2) will ever be able to deliver m. Uniform Agreement is violated, but not (nonuniform) Agreement: no *correct* process ever delivers m (p_1 is not correct).

Note 1. *Byzantine failures and uniformity.* Algorithms tolerant to Byzantine failures can guarantee none of the uniform properties given in Section 2.3. This is understandable as no behavior

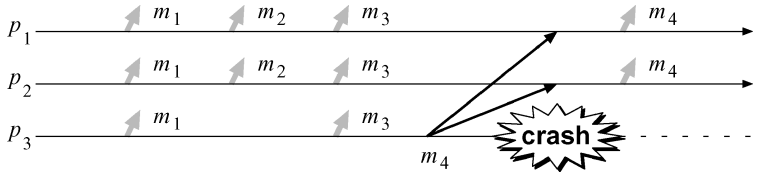


Fig. 2. Contamination of correct processes (p_1, p_2), by a message (m_4), based on an inconsistent state (p_3 delivered m_3 but not m_2).

can be enforced on Byzantine processes. In other words, nothing can prevent a Byzantine process from (1) delivering a message more than once (violates Uniform Integrity), (2) delivering a message that is not delivered by other processes (violates Agreement), or (3) delivering two messages in the wrong order (violates Total Order).

Reiter [1994] proposes a more useful definition of uniformity for Byzantine systems. He distinguishes between crashes and Byzantine failures. He says that a process is *honest* if it behaves according to its specification, and *corrupt* otherwise (i.e., Byzantine), where honest processes can also fail by crashing. In this context, uniform properties are those which are enforced by all honest processes, regardless of whether they are correct or not. This definition is more sensible that the stricter of definition of Section 2.3, as nothing is required from corrupt processes.

Note 2. *Safety/liveness and uniformity.* Charron-Bost et al. [2000] have shown that, in the context of failures, some nonuniform properties that are commonly believed to be safety properties are actually liveness properties. They have proposed refinements of the concept of safety and liveness that avoid the counterintuitive classification.

2.5. Contamination

The problem of contamination comes from the observation that, even with the strongest specification (i.e., with Uniform Agreement and Uniform Total Order), total order broadcast does not prevent a faulty process p from reaching an inconsistent state before it crashes. This is a serious problem because p can "legally" TO-broadcast a message based on this inconsistent state, and thus *contaminate* correct processes [Gopal and Toueg 1991; Anceaume and Minet 1992; Anceaume 1993b; Hadzilacos and Toueg 1994].

2.5.1. Illustration. Figure 2 illustrates an example [Charron-Bost et al. 1999; Hadzilacos and Toueg 1994] in which an incorrect process contaminates the correct processes. Process p_3 delivers messages m_1 and m_3, but not m_2. So, its state is inconsistent when it multicasts m_4 to the other processes before crashing. The correct processes p_1 and p_2 deliver m_4, thus becoming contaminated by the inconsistent state of p_3. It is important to stress again that the situation depicted in Figure 2 satisfies even the strongest specification presented so far.

2.5.2. Specification. It is possible to extend or reformulate the specification of total order broadcast in such a way that it disallows contamination. The solution consists of preventing any process from delivering a message that may lead to an inconsistent state.

Aguilera et al. [2000] propose a reformulation of Uniform Total Order which, unlike the traditional definition, is not prone to contamination, as it does not allow gaps in the delivery sequence:

(GAP-FREE UNIFORM TOTAL ORDER) If some process delivers message m' after message m, then a process delivers m' only after it has delivered m.

As an alternative, an older formulation uses the history of delivery and requires that, for any two given processes, the history of one is a prefix of the history of the other. This is expressed by the following property [Anceaume and Minet 1992; Cristian et al. 1994; Keidar and Dolev 2000]:

(PREFIX ORDER) For any two processes p and q, either $hist(p)$ is a prefix of $hist(q)$, or $hist(q)$ is a prefix of $hist(p)$, where $hist(p)$ and $hist(q)$ are the sequences of messages delivered by p and q, respectively.

Note 3. The specification of total order broadcast using Prefix Order precludes the dynamic join of processes (e.g., with a group membership). This can be circumvented, but the resulting property is much more complicated. For this reason, the simpler alternative proposed by Aguilera et al. [2000] is preferred.

Note 4. *Byzantine failures and contamination.* Contamination cannot be avoided in the face of arbitrary failures. This is because a faulty process may be inconsistent even if it delivers all messages correctly. It may then contaminate the other processes by broadcasting a bogus message that seems correct to every other process [Hadzilacos and Toueg 1994].

2.6. Other Ordering Properties

The Total Order property (see Section 2.3), restricts the order of message delivery based solely on the destinations, that is, the property is independent of the sender processes. The definition can be further restricted by two properties related to the senders, namely, *FIFO Order* and *Causal Order*.

2.6.1. FIFO Order. Total Order alone does not guarantee that messages are delivered in the order in which they are sent (i.e., in first-in/first-out order). Yet, this property is sometimes required by applications in addition to Total Order. The property is called FIFO Order:

(FIFO ORDER) If a correct process TO-broadcasts a message m before it TO-broadcasts a message m', then no correct process delivers m', unless it has previously delivered m.

2.6.2. Causal Order. The notion of causality in the context of distributed systems was first formalized by Lamport [1978b]. It is based on the relation "precedes"[3] (denoted by $\longrightarrow$), defined in his seminal paper and extended in a later paper [Lamport 1986b]. The relation "precedes" is defined as follows.

Definition 1. Let e_i and e_j be two events in a distributed system. The transitive relation $e_i \longrightarrow e_j$ holds if any one of the following three conditions is satisfied:

(1) e_i and e_j are two events on the same process, and e_i comes before e_j;
(2) e_i is the sending of a message m by one process, and e_j is the receipt of m by another process; or,
(3) There exists a third event e_k, such that, $e_i \longrightarrow e_k$ and $e_k \longrightarrow e_j$ (transitivity).

This relation defines an irreflexive partial ordering on the set of events. The causality of messages can be defined by the "precede" relationship between their respective sending events. More precisely, a message m is said to precede a message m' (denoted $m \prec m'$), if the sending event of m precedes the sending event of m'.

The property of causal order for broadcast messages is defined as follows [Hadzilacos and Toueg 1994]:

(CAUSAL ORDER) If the broadcast of a message m causally precedes the broadcast of a message m', then no correct process delivers m', unless it has previously delivered m.

Hadzilacos and Toueg [1994] also prove that the property of Causal Order is equivalent to combining the property of FIFO Order with the following property of Local Order.

(LOCAL ORDER) If a process broadcasts a message m and a process delivers m before broadcasting m', then no correct process delivers m', unless it has previously delivered m.

Note 5. *State-machine approach.* A total order broadcast ensuring causal order

[3]Lamport initially called the relation "happened before" [Lamport 1978b], but he renamed it "precedes" in later work [Lamport 1986a, 1986b].

is, for instance, required by the state machine approach [Lamport 1978a; Schneider 1990]. However, we think that some applications may require causality, some others not.

2.6.3. Source Ordering. Some papers (e.g., Garcia-Molina and Spauster [1991] and Jia [1995]) make a distinction between single source and multiple source ordering. These papers define single source ordering algorithms as algorithms that ensure total order only if a *single* process broadcasts messages. This is a special case of FIFO broadcast, easily solved using sequence numbers. Source ordering is not particularly interesting in itself, and hence we do not discuss the issue further in this article.

3. PROPERTIES OF DESTINATION GROUPS

So far, we have presented the problem of total order broadcast, wherein messages are sent to all processes in the system. In other words, all valid messages are addressed to the entire system:

$$\forall m \in \mathcal{M}\ (Dest(m) = \Pi). \tag{3}$$

A *multicast* primitive is more general in the sense that it can send messages to any chosen subset of the processes. In other words, we can have two valid messages sent to different destinations sets, or the destination set may not include the message sender:

$$\exists m \in \mathcal{M}\ (sender(m) \notin Dest(m)) \wedge \exists m_i, m_j \in \mathcal{M}\ (Dest(m_i) \neq Dest(m_j)). \tag{4}$$

Although in wide use, the distinction between broadcast and multicast is not precise enough. This leads us to discuss a more relevant distinction, namely, between closed versus open groups, and between single versus multiple groups.

3.1. Closed Versus Open Groups

In the literature, many algorithms are designed with the implicit assumption that messages are sent *within* a group of processes. This originally came from the fact that early work on this topic was done in the context of parallel machines [Lamport 1978a], or highly available storage systems [Cristian et al. 1995]. However, most distributed applications are now developed by considering more open interaction models, such as the client-server model, N-tier architectures, or publish/subscribe. For this reason, it is necessary for a process to be able to multicast messages to a group to which it does not belong. Consequently, we consider it an important characteristic of algorithms that they be easily adaptable to open interaction models.

3.1.1. Closed Group Algorithms. In closed groups algorithms, the sending process is always one of the destination processes:

$$\forall m \in \mathcal{M}\ (sender(m) \in Dest(m)). \tag{5}$$

So, these algorithms do not allow external processes (processes that are not members of the group) to multicast messages to the destination group.

3.1.2. Open Group Algorithms. Conversely, open group algorithms allow any arbitrary process in the system to multicast messages to a group, whether or not the sender process belongs to the destination group. More precisely, there are some valid messages where the sender is not one of the destinations:

$$\exists m \in \mathcal{M}\ (sender(m) \notin Dest(m)). \tag{6}$$

Open group algorithms are more general than closed group algorithms: the former can be used with closed groups, while the opposite is not true.

3.2. Single Versus Multiple Groups

Most algorithms presented in the literature assume that all messages are multicast to one single group of destination processes. Nevertheless, a few algorithms are designed to support multiple groups. In this context, we consider three situations: *single group*, *multiple disjoint groups*, and

multiple overlapping groups. We also discuss how useless, trivial solutions can be ruled out with the notion of *minimality*. Since the ability to multicast messages to multiple destination sets is critical for certain classes of applications, we regard this ability as an important characteristic of an algorithm.

3.2.1. Single Group Ordering. With single group ordering, all messages are multicast to one single group of destination processes. As mentioned above, this is the model considered by a vast majority of the algorithms that are studied in this article. Single group ordering can be defined by the following property:[4]

$$\forall m_i, m_j \in \mathcal{M}\,(Dest(m_i) = Dest(m_j)). \quad (7)$$

3.2.2. Multiple Groups Ordering (Disjoint). In some applications, the restriction to one single destination group is not acceptable. For this reason, algorithms have been proposed that support multicasting messages to multiple groups. The simplest case occurs when the multiple groups are *disjoint* groups. More precisely, if two valid messages have different destination sets, then these sets do not intersect:

$$\begin{aligned}\forall m_i, m_j \;&\in\; \mathcal{M}\,(Dest(m_i) \neq Dest(m_j)\\ &\Rightarrow\; Dest(m_i) \cap Dest(m_j) = \emptyset).\end{aligned} \quad (8)$$

Adapting algorithms designed for one single group to work in a system with multiple disjoint groups is almost trivial.

3.2.3. Multiple Groups Ordering (Overlapping). In case of multiple groups ordering, it can happen that groups overlap. This can be expressed by the fact that some pairs of valid messages have different destination sets with a nonempty intersection:

$$\begin{aligned}\exists m_i, m_j \;&\in\; \mathcal{M}\,(Dest(m_i) \neq Dest(m_j)\\ &\wedge\; Dest(m_i) \cap Dest(m_j) \neq \emptyset).\end{aligned} \quad (9)$$

The real difficulty of designing total order multicast algorithms for multiple groups arises when the groups can overlap. This is easily understood when one considers the problem of ensuring total order at the intersection of groups. In this context, Hadzilacos and Toueg [1994] give three different properties for total order in the presence of multiple groups: *Local Total Order*, *Pairwise Total Order*, and *Global Total Order*.[5]

(Local Total Order) If correct processes p and q both TO-deliver messages m and m' and $Dest(m) = Dest(m')$, then p TO-delivers m before m', if and only if q TO-delivers m before m'.

Local Total Order is the weakest of the three properties. It requires that total order be enforced only for messages that are multicast within the same group.

Note also that multiple unrelated groups can be considered as disjoint groups even if they overlap. Indeed, destination processes belonging to the intersection of two groups can be seen as having two distinct identities, one for each group. It follows that an algorithm for distinct multiple groups can be trivially adapted to support overlapping groups with Local Total Order.

As pointed out by Hadzilacos and Toueg [1994], the total order multicast primitive of the first version of Isis [Birman and Joseph 1987] guaranteed Local Total Order.[6]

(Pairwise Total Order) If two correct processes p and q both TO-deliver messages m and m', then p TO-delivers m

[4]This definition and the following ones are static. They do not take into account the fact that processes can join groups and leave groups. Nevertheless, we prefer these simple static definitions, rather than more complex ones that would take dynamic destination groups into account.

[5]The ordering properties cited here are subject to contamination, see Section 2.5. Contamination can be avoided by formulating these properties similarly to the Gap-free Uniform Total Order property.

[6]It should be noted that, if the transformation is trivial from a conceptual point of view, the implementation was certainly a totally different matter, especially in the mid-80's.

before m', if and only if q TO-delivers m before m'.

Pairwise Total Order is strictly stronger than Local Total Order. Most notably, it requires that total order be enforced for all messages delivered at the intersection of two groups.

As far as we know, there is no straightforward algorithm to transform a total order multicast algorithm that enforces Local Total Order into one that also guarantees Pairwise Total Order (except for trivial solutions; see Section 3.2.4). Hadzilacos and Toueg [1994] observe that, for instance, Pairwise Total Order is the order property guaranteed by the algorithm of Garcia-Molina and Spauster [1989, 1991].

Pairwise Total Order alone may lead to unexpected situations when there are three or more overlapping destination groups. For instance, Fekete [1993] illustrates the problem with the following scenario. Consider three processes p_i, p_j, p_k, and three messages m_1, m_2, m_3 that are respectively sent to three different overlapping groups $G_1 = \{p_i, p_j\}$, $G_2 = \{p_j, p_k\}$, and $G_3 = \{p_k, p_i\}$. Pairwise Total Order allows the following histories on p_i, p_j, p_k:

$$\begin{aligned} p_i &: \cdots \textit{TO-deliver}(m_3) \longrightarrow \cdots \\ &\qquad \longrightarrow \textit{TO-deliver}(m_1) \cdots \\ p_j &: \cdots \textit{TO-deliver}(m_1) \longrightarrow \cdots \\ &\qquad \longrightarrow \textit{TO-deliver}(m_2) \cdots \\ p_k &: \cdots \textit{TO-deliver}(m_2) \longrightarrow \cdots \\ &\qquad \longrightarrow \textit{TO-deliver}(m_3) \cdots \end{aligned}$$

This situation is prevented by the specification of Global Total Order [Hadzilacos and Toueg 1994], which is defined as follows:

(GLOBAL TOTAL ORDER) The relation $<$ is acyclic, where $<$ is defined as follows: $m < m'$ if and only if any correct process delivers m and m', in that order.

Note 6. Fekete [1993] gives another specification for total order multicast which also prevents the scenario just mentioned. The specification, called AMC, is expressed as an I/O automaton [Lynch and Tuttle 1989; Lynch 1996] and uses the notion of pseudo-time to impose an order on the delivery of messages.

3.2.4. Minimality and Trivial Solutions. Any algorithm that solves the problem of total order broadcast in a single group can easily be adapted to solve the problem for multiple groups with the following approach:

(1) form a super-group with the union of all destination groups;
(2) whenever a message m is multicast to a group, multicast it to the super-group, and
(3) processes not in $Dest(m)$ discard m.

The problem with this approach is its inherent lack of scalability. Indeed, in very large distributed systems, even if the destination groups are individually small, their union is likely to cover a very large number of processes.

To avoid this sort of solution, Guerraoui and Schiper [2001] require the implementation of total order multicast for multiple groups to satisfy the following minimality property:

(STRONG MINIMALITY) The execution of the algorithm implementing total order multicast for a message m involves only $sender(m)$, and the processes in $Dest(m)$.

This property is often too strong: it disallows many interesting algorithms that use a small number of external processes for message-ordering (e.g., algorithms which disseminate messages along some propagation tree). A weaker property would allow an algorithm to involve a small set of external processes.

3.2.5. Transformation Algorithm. Delporte-Gallet and Fauconnier [2000] propose a generic algorithm that transforms a total order broadcast algorithm for a single closed group into one for multiple groups. The algorithm splits destination groups into smaller entities and supports multiple groups with Strong Minimality.

3.3. Dynamic Groups

The specification in Section 2 is the standard specification of total order broadcast in a *static* system, that is, a system in which all processes are created at system initialization. In practice, however, it is often desirable that processes join and leave groups at runtime.

A *dynamic* group is a group of processes with a membership that can change during the computation: processes can dynamically join or leave the group, or can be removed from the group (removal in the face of failures is discussed later in Section 6.2). With a dynamic group, the successive memberships of the group are called the *views* of the group [Chockler, Keidar, and Vitenberg 2001].

With dynamic groups, the basic communication abstraction is called *view synchrony*, which can be seen as the counterpart of reliable broadcast in static systems. Reliable broadcast is defined by the Validity, Agreement, and Uniform Integrity properties of Section 2. Roughly speaking, view synchrony adopts a similar definition, while relaxing the Agreement property.[7] Total order broadcast in a system with dynamic groups can thus be specified as view synchrony, plus a property of total order.

3.4. Partitionable Groups

In a wide-area network, the network can temporarily become partitioned; that is, some of the nodes can no longer communicate, as all links between them are broken. When this happens, destination groups can be split into several isolated subgroups (or partitions). There are two main approaches to coping with partitioned groups: (1) the *primary partition* membership, and (2) the *partitionable* membership.

With the primary partition membership, one of the partitions is recognized as the primary partition.[8] Only processes that belong to the primary partition are allowed to deliver messages, while the other processes must wait until they can merge back with the primary partition.

In contrast, the partitionable group membership allows all processes to deliver messages, regardless of the partition they belong to. Doing so requires adapting the specification of total order broadcast. Chockler, Keidar, and Vitenberg [2001] define three order properties in a partitionable system: Strong Total Order (messages are delivered in the same order by all processes that deliver them), Weak Total Order (the order requirement is restricted within a view), and Reliable Total Order (extends the Strong Total Order property to require processes to deliver a prefix of a common sequence of messages within each view). In other words, with only slight differences, Strong Total Order corresponds to the Uniform Total Order property of Section 2.3, and Reliable Total Order to the Prefix Ordering property of Section 2.5. Other properties, such as Validity, are also defined differently in partitionable systems. This is explained in considerably more detail by Chockler, Keidar, and Vitenberg [2001] and Fekete et al. [2001].

4. MECHANISMS FOR MESSAGE ORDERING

In this section, we propose a classification of total order broadcast algorithms in the absence of failures. The first question that we ask is: "who builds the order?" More specifically, we are interested in the entity that generates the information necessary for defining the order of messages (e.g., timestamp or sequence number).

We identify three different roles that a participating process can take with respect to the algorithm: sender, destination, or sequencer. A *sender* process is a process p_s from which a message originates (i.e., $p_s \in \Pi_{sender}$). A *destination* process is

[7] Discussing this primitive in detail is beyond the scope of this survey (see paper by Chockler, Keidar, and Vitenberg [2001] for details).

[8] A simple way to do this is to recognize as primary partition only one which retains a majority of the processes from the previous view. This does not ensure that a primary partition always exists, but it guarantees that, if one exists, it is unique.

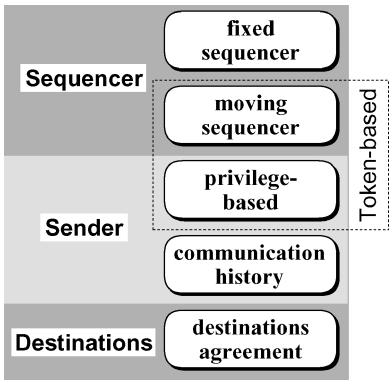


Fig. 3. Classes of total order broadcast algorithms.

a process p_d to which a message is sent (i.e., $p_d \in \Pi_{dest}$). Finally, a *sequencer* process is not necessarily a sender or a destination, but is somehow involved in the ordering of messages. A given process may simultaneously take several roles (e.g., sender *and* sequencer *and* destination). However, we represent these roles separately as they are conceptually different.

According to the three different roles, we define three basic classes for total order broadcast algorithms, depending on whether the order is respectively built by a sequencer, the sender, or destination processes. Among algorithms of the same class, significant differences remain. To account for this problem, we introduce a further division, leading to five subclasses in total. These classes are named as follows (see Figure 3): *fixed sequencer*, *moving sequencer*, *privilege-based*, *communication history*, and *destinations agreement*. Privilege-based and moving sequencer algorithms are commonly referred to as token-based algorithms.

The terminology defined in this article is partly borrowed from other authors. For instance, "communication history" and "fixed sequencer" were proposed by Cristian and Mishra [1995]. The term "privilege-based" was suggested by Dahlia Malkhi in a private discussion. Finally, Le Lann and Bres [1991] group algorithms into three classes, based on where the order is built. Unfortunately, their definition

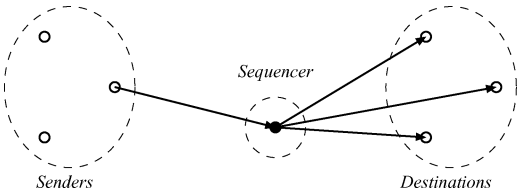


Fig. 4. Fixed sequencer algorithms.

of classes is specific to a client-server architecture.

In the remainder of this section, we present each of the five classes and illustrate each class with a simple algorithm. The algorithms are merely presented for the purpose of illustrating the corresponding category, and should not be regarded as full-fledged working examples. Although inspired by existing algorithms, they are largely simplified, and none of them is fault-tolerant.

Note 7. *Atomic blocks*. The algorithms are written in pseudocode, with the assumption that blocks associated with a when-clause are executed atomically with respect to when-clauses of the same process, except when a process is blocked on a wait statement. This assumption greatly simplifies the expression of the algorithms with respect to concurrency.

4.1. Fixed Sequencer

In a fixed sequencer algorithm, one process is elected as the sequencer and is responsible for ordering messages. The sequencer is unique, and the responsibility is not normally transfered to another processes (at least in the absence of failure).

The approach is illustrated in Figure 4 and Figure 5. One specific process takes the role of a sequencer and builds the total order. To broadcast a message m, a sender sends m to the sequencer. Upon receiving m, the sequencer assigns it a sequence number and relays m with its sequence number to the destinations. The latter then deliver messages according to the sequence numbers. This algorithm does not tolerate the failure of the sequencer.

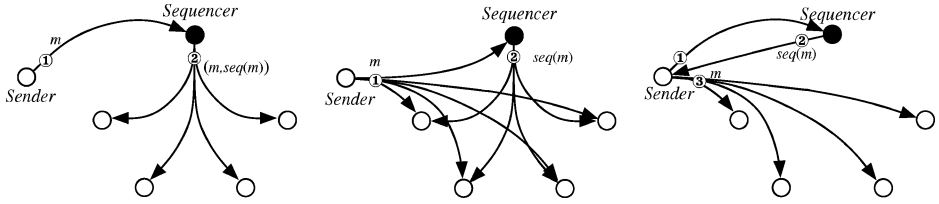
In fact, three variants of fixed sequencer algorithms exist. We call these three variants "UB" (unicast-broadcast),

```
Sender:
    procedure TO-broadcast(m)                    { To TO-broadcast a message m }
        send (m) to sequencer

Sequencer:
    Initialization:
        seqnum := 1
    when receive (m)
        sn(m) := seqnum
        send (m, sn(m)) to all
        seqnum := seqnum + 1

Destinations (code of process p_i):
    Initialization:
        nextdeliver_{p_i} := 1
        pending_{p_i} := ∅
    when receive (m, seqnum)
        pending_{p_i} := pending_{p_i} ∪ {(m, seqnum)}
        while ∃(m', seqnum') ∈ pending_{p_i} : seqnum' = nextdeliver_{p_i} do
            deliver (m')
            nextdeliver_{p_i} := nextdeliver_{p_i} + 1
```

Fig. 5. Simple fixed sequencer algorithm.



(a) variant UB (b) variant BB (c) variant UUB

Fig. 6. Common variants of fixed sequencer algorithms.

"BB" (broadcast-broadcast), and "UUB" (unicast-unicast-broadcast), taking inspiration from Kaashoek and Tanenbaum [1996].

In the first variant, called "UB" (see Figure 6(a)), the protocol consists of a unicast to the sequencer, followed by a broadcast from the sequencer. This variant generates few messages, and it is the simplest of the three approaches. It is, for instance, adopted by Navaratnam et al. [1988], and corresponds to the algorithm in Figure 5.

In the second variant, called "BB" (Figure 6(b)), the protocol consists of a broadcast to all destinations plus the sequencer, followed by a second broadcast from the sequencer. This generates more messages than the previous approach, except in broadcast networks. However, it can reduce the load on the sequencer, and makes it easier to tolerate the crash of the sequencer. Isis (sequencer) [Birman et al. 1991] is an example of the second variant.

The third variant, called "UUB" (Figure 6(c)), is less common than the others. In short, the protocol consists of the following steps. The sender requests a sequence number from the sequencer (unicast). The sequencer replies with a sequence number (unicast). Then, the sender broadcasts the sequenced message to the destination processes.[9]

[9]The protocol to tolerate failures is complex.

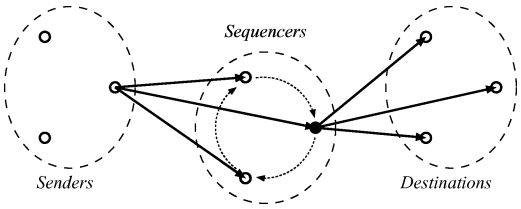


Fig. 7. Moving sequencer algorithms.

4.2. Moving Sequencer

Moving sequencer algorithms are based on the same principle as fixed sequencer algorithms, but allow the role of sequencer to be transferred between several processes. The motivation is to distribute the load among them. This is illustrated in Figure 7, where the sequencer is chosen among several processes. The code executed by each process is, however, more complex than with a fixed sequencer, which explains the popularity of the latter approach. Notice that with moving sequencer algorithms, the roles of sequencer and destination processes are normally combined.

Figure 8 shows the principle of moving sequencer algorithms. To broadcast a message m, a sender sends m to the sequencers. Sequencers circulate a token message that carries a sequence number and a list of all messages to which a sequence number has been attributed (i.e., all sequenced messages). Upon receipt of the token, a sequencer assigns a sequence number to all received, but yet unsequenced, messages. It sends the newly sequenced messages to the destinations, updates the token, and passes it to the next sequencer.

Note 8. Similar to fixed sequencer algorithms, it is possible to develop a moving sequencer algorithm according to one of three variants. However, the difference between the variants is not as clear cut as it is for a fixed sequencer. It turns out that all of the moving sequencer algorithms surveyed follow the equivalent of the fixed sequencer variant BB. Hence, we do not discuss this issue any further.

Note 9. As mentioned, the main motivation for using a moving sequencer is to distribute the load among several processes, thus avoiding the bottleneck caused by a single process. This is illustrated in several studies (e.g., Cristian et al. [1994] and Urbán et al. [2000]). One could then wonder why a fixed sequencer algorithm should be preferred to a moving sequencer algorithm. There are, in fact, at least three possible reasons. First, fixed sequencer algorithms are considerably simpler, leaving less room for implementation errors. Second, the latency of fixed sequencer algorithms is often better, as shown by Urbán et al. [2000]. Third, it is often the case that some machines are more reliable, more trusted, better connected, or simply faster than others. When this is the case, it makes sense to use one of them as a fixed sequencer (see MTP in Section 7.1.2).

4.3. Privilege-Based

Privilege-based algorithms rely on the idea that senders can broadcast messages only when they are granted the privilege to do so. Figure 9 illustrates this class of algorithms. The order is defined by the senders when they broadcast their messages. The privilege to broadcast (and order) messages is granted to only one process at a time, but this privilege circulates from process to process, among the senders. In other words, due to the arbitration between senders, building the total order requires solving the problem of FIFO broadcast (easily solved with sequence numbers at the sender), and ensuring that passing the privilege to the next sender does not violate this order.

Figure 10 illustrates the principle of privilege-based algorithms. Senders circulate a token message that carries a sequence number to be used when broadcasting the next message. When a process wants to broadcast a message m, it must first wait until it receives the token message. Then, it assigns a sequence number to each of its messages and sends them to all destinations. Following this, the sender updates the token and sends it to the next sender. Destination processes deliver messages in increasing sequence numbers.

```
Sender:
    procedure TO-broadcast(m)                    { To TO-broadcast a message m }
        send (m) to all sequencers

Sequencers (code of process s_i):
    Initialization:
        received_{s_i} := ∅
        if s_i = s_1 then
            token.seqnum := 1
            token.sequenced := ∅
            send token to s_1
    when receive m
        received_{s_i} := received_{s_i} ∪ {m}
    when receive token from s_{i-1}
        for each m' in received_{s_i} \ token.sequenced do
            send (m', token.seqnum) to destinations
            token.seqnum := token.seqnum + 1
            token.sequenced := token.sequenced ∪ {m'}
        send token to s_{i+1 (mod n)}

Destinations (code of process p_i):
    Initialization:
        nextdeliver_{p_i} := 1
        pending_{p_i} := ∅
    when receive (m, seqnum)
        pending_{p_i} := pending_{p_i} ∪ {(m, seqnum)}
        while ∃(m', seqnum') ∈ pending_{p_i} s.t. seqnum' = nextdeliver_{p_i} do
            deliver (m')
            nextdeliver_{p_i} := nextdeliver_{p_i} + 1
```

Fig. 8. Simple moving sequencer algorithm.

Note 10. In privilege-based algorithms, senders usually need to know each other in order to circulate the privilege. This constraint makes privilege-based algorithms poorly suited to open groups, where there is no fixed and previously known set of senders.

Note 11. In synchronous systems, privilege-based algorithms are based on the idea that each sender process is allowed to send messages only during predetermined time slots. These time slots are attributed to each process in such a way that no two processes can send messages at the same time. By ensuring that the communication medium is accessed in mutual exclusion, the total order is easily guaranteed. The technique is also known as *time division multiple access* (TDMA).

Note 12. It is tempting to consider that privilege-based and moving sequencer algorithms are equivalent, since both rely on a token passing mechanism. However, they differ in one significant aspect: the total order is built by senders in privilege-based algorithms, while it is built by sequencers in moving sequencer algorithms. This has at least two major consequences. First, moving sequencer algorithms are easily adapted to open groups. Second, in privilege-based algorithms, the passing of the token is necessary to ensure the liveness of the algorithm, while with moving sequencer algorithms, it is mostly used for

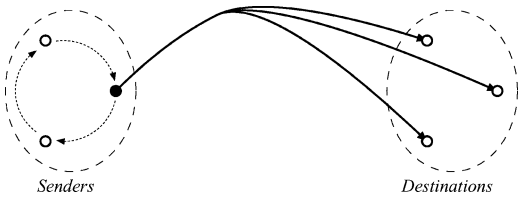


Fig. 9. privilege-based algorithms.

```
Senders (code of process s_i):
    Initialization:
        tosend_{s_i} := ∅
        if s_i = s_1 then
            token.seqnum := 1
            send token to s_1
    procedure TO-broadcast(m)                    { To TO-broadcast a message m }
        tosend_{s_i} := tosend_{s_i} ∪ {m}
    when receive token
        for each m' in tosend_{s_i} do
            send (m', token.seqnum) to destinations
            token.seqnum := token.seqnum + 1
        tosend_{s_i} := ∅
        send token to s_{i+1 (mod n)}

Destinations (code of process p_i):
    Initialization:
        nextdeliver_{p_i} := 1
        pending_{p_i} := ∅
    when receive (m, seqnum)
        pending_{p_i} := pending_{p_i} ∪ {(m, seqnum)}
        while ∃(m', seqnum') ∈ pending_{p_i} s.t. seqnum' = nextdeliver_{p_i} do
            deliver (m')
            nextdeliver_{p_i} := nextdeliver_{p_i} + 1
```

Fig. 10. Simple privilege-based algorithm.

improving performance, for example, by load balancing.

Note 13. It is difficult to ensure fairness with privilege-based algorithms. Indeed, if a process has a very large number of messages to broadcast, it could keep the token for an arbitrarily long time, thus preventing other processes from broadcasting their own messages. To overcome this problem, algorithms often enforce an upper limit on the number of messages and/or the time that some process can keep the token. Once the limit is passed, the process is compelled to release the token, regardless of the number of messages remaining to be broadcast.

4.4. Communication History

In communication history algorithms, as in privilege-based algorithms, the delivery order is determined by the senders. However, in contrast to privilege-based algorithms, processes can broadcast messages at any time, and total order is ensured by delaying the delivery of messages. The messages usually carry a (physical or logical) timestamp. The destinations observe the messages generated by the other processes and their timestamps, that is, the history of communication in the system, to learn when delivering a message will no longer violate the total order.

There are two fundamentally different variants of communication history algorithms. In the first variant, called *causal history*, communication history algorithms use a partial order, defined by the causal history of messages, and transform this partial order into a total order. Concurrent messages are ordered according to some predetermined function. In the second variant, known as *deterministic merge*, processes send messages timestamped independently (thus not reflecting causal order), and delivery takes place according to a deterministic policy of merging the streams of messages coming from each process.

Figure 11 illustrates a typical communication history algorithm of the first variant. The algorithm, inspired by Lamport [1978b], works as follows. The algorithm uses logical clocks [Lamport 1978b] to

```
Senders and destinations (code of process p; assumes FIFO channels):
    Initialization:
        received_p := ∅                                   { Messages received by process p }
        delivered_p := ∅                                  { Messages delivered by process p }
        LC_p[p_1 ... p_n] := {0, ..., 0}    { LC_p[q]: logical clock of process q, as seen by p }
    procedure TO-multicast(m)                             { To TO-multicast a message m }
        LC_p[p] := LC_p[p] + 1
        ts(m) := LC_p[p]
        send FIFO (m, ts(m)) to all
    when receive (m, ts(m))
        LC_p[p] := max(ts(m), LC_p[p]) + 1
        LC_p[sender(m)] := ts(m)
        received_p := received_p ∪ {m}
        deliverable := ∅
        for each message m' in received_p \ delivered_p do
            if ts(m') ≤ min_{q∈Π} LC_p[q] then
                deliverable := deliverable ∪ {m'}
        deliver all messages in deliverable, in increasing order of (ts(m), sender(m))
        delivered_p := delivered_p ∪ deliverable
```

Fig. 11. Simple communication history algorithm (causal history).

```
Senders and destinations (assumes FIFO channels):
    procedure TO-multicast(m)                             { To TO-multicast a message m }
        send FIFO (m) to all
    forever do
        for each process p in Π_sender do
            wait until receive m' from p
            deliver (m')
```

Fig. 12. Simple communication history algorithm (deterministic merge).

"timestamp" each message m with the logical time of the *TO-broadcast*(m) event, denoted $ts(m)$. Messages are then delivered in the order of their timestamps. However, we can have two messages, m and m', with the same timestamp. To arbitrate between these messages, the algorithm uses the lexicographical order on the identifiers of sending processes. In Figure 11, we refer to this order as the ($ts(m)$, $sender(m)$) order, where $sender(m)$ is the identifier of the sender process.

A simple example of the second variant is illustrated in Figure 12. The algorithm assumes that communication is FIFO, and that sender processes broadcast messages at the same rate. Destination processes execute an infinite loop where they accept, in a round-robin fashion, a single message from each sender process. Aguilera and Strom [2000] (Section 7.4.9), for instance, propose a more elaborate algorithm based on the same principle.

Note 14. The algorithms of Figure 11 and Figure 12 are not live. Indeed, consider the algorithm of Figure 11 and a scenario where a single process p broadcasts a single message m, while no other process ever broadcasts any message. According to the algorithm in Figure 11, a process q can deliver m only after it has received, from every process, a message that was broadcast *after* the reception of m. This is, of course, impossible if at least one of the processes never broadcasts any message. To overcome this problem, communication history algorithms proposed in the literature usually send empty messages when no application messages are broadcast.

Note 15. In synchronous systems, communication history algorithms rely on synchronized clocks, and use physical timestamps (timestamps coming from the synchronized clocks), instead of logical ones. The nature of such systems makes

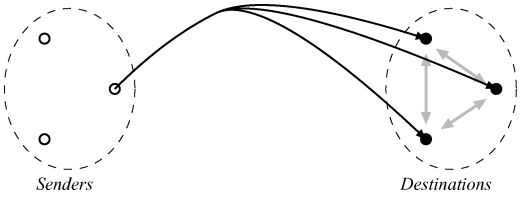


Fig. 13. Destinations agreement algorithms.

it unnecessary to send empty messages in order to ensure liveness. Indeed, this can be seen as an example of the use of time to communicate [Lamport 1984].

4.5. Destinations Agreement

In destinations agreement algorithms, as the name indicates, the delivery order results from an agreement between destination processes (see Figure 13). We distinguish three different variants of agreement: (1) agreement on a message sequence number, (2) agreement on a message set, or (3) agreement on the acceptance of a proposed message order.

Figure 14 illustrates an algorithm of the first variant: for each message, the destination processes reach an agreement on a unique (yet not consecutive) sequence number. The algorithm is adapted from Skeen's algorithm (Section 7.5.1), although it operates in a decentralized manner. Briefly, the algorithm works as follows. To broadcast a message m, a sender sends m to all destinations. Upon receiving m, a destination assigns it a local timestamp and sends this timestamp to all destinations. Once a destination process has received a local timestamp for m from all destinations, a unique global timestamp $sn(m)$ is assigned to m, calculated as the maximum of all local timestamps. Messages are delivered in the order of their global timestamp, that is, a message m can only be delivered once it has been assigned its global timestamp $sn(m)$, and no other undelivered message m' can possibly receive a timestamp $sn(m')$ smaller or equal to $sn(m)$. As with the communication history algorithm (Figure 11), the identifier of the message sender is used to break ties between messages with the same global timestamp.

The most representative algorithm of the second variant of agreement is the algorithm proposed by Chandra and Toueg [1996] (Section 7.5.4). The algorithm transforms total order broadcast into a sequence of *consensus* problems.[10] Each instance of the consensus decides on a set of messages to deliver, that is, consensus number k allows the processes to agree on a set Msg^k of messages. For $k < k'$, the messages in Msg^k are delivered before the messages in $Msg^{k'}$. The messages in a set Msg^k are delivered according to some predetermined order (e.g., in lexical order of their identifiers).

With the third variant of agreement, a tentative message delivery order is first proposed (usually by one of the destinations). Then, the destination processes must agree to either accept or reject the proposal. In other words, this variant of destinations agreement relies on an atomic commitment protocol. The algorithm proposed by Luan and Gligor [1990] typically belongs to the third variant.

Note 16. There is a thin line between the second and the third variants of agreement. For instance, Chandra and Toueg's [1996] total order broadcast algorithm relies on consensus, as described. However, when it is combined with the rotating coordinator consensus algorithm [Chandra and Toueg 1996], the resulting algorithm can be seen as an algorithm of the third form. Indeed, the coordinator proposes a tentative order (given as a set of message plus message identifiers) that it tries to validate. Thus it is important to note that two seemingly identical algorithms may use different forms of agreement, simply because they are described at different levels of abstraction.

4.6. Time-Free Versus Time-Based Ordering

We introduce a further distinction between algorithms, orthogonal to the above

[10]The consensus problem is informally defined as follows: every process proposes some value, and all processes must eventually decide on the same value, which must be one (any one) of the proposed values.

```
Sender:
    procedure TO-broadcast(m)                          { To TO-broadcast a message m }
        send (m) to destinations

Destinations (code of process p_i):
    Initialization:
        stamped_{p_i} := ∅
        received_{p_i} := ∅
        LC_{p_i} := 0                                  { LC_{p_i}: logical clock of process p_i }
    when receive m
        ts_i(m) := LC_{p_i}
        received_{p_i} := received_{p_i} ∪ {(m, ts_i(m))}
        send (m, ts_i(m)) to destinations
        LC_{p_i} := LC_{p_i} + 1
    when received (m, ts_j(m)) from p_j
        LC_{p_i} := max(ts_j, LC_{p_i} + 1)
        if received (m, ts(m)) from all destinations then
            sn(m) := max_{k=1...n} ts_k(m)
            stamped_{p_i} := stamped_{p_i} ∪ {(m, sn(m))}
            received_{p_i} := received_{p_i} \ {m}
            deliverable := ∅
            for each (m', sn(m')) ∈ stamped_{p_i} s.t. ∀m'' ∈ received_{p_i} : sn(m') < ts_i(m'') do
                deliverable := deliverable ∪ {(m', sn(m'))}
            deliver all messages in deliverable in increasing order of (sn(m), sender(m))
            stamped_{p_i} := stamped_{p_i} \ deliverable
```

Fig. 14. Simple destinations agreement algorithm.

classification. The distinction is between algorithms that use physical time for message ordering, and algorithms that do not use physical time. For instance, in Section 4.4 (see Figure 11), we presented a simple communication-history algorithm based on *logical* time. It is indeed possible to design a similar algorithm that uses the *physical* time (and synchronized clocks) instead.

In short, we distinguish algorithms with *time-based ordering*, that rely on physical time, and algorithms with *time-free ordering* that do not use physical time.

5. CONCEPTUAL ISSUES RELATED TO FAILURES

In Section 4, we discussed ordering mechanisms, ignoring the problem of failures. Mechanisms for fault-tolerance are discussed below in Section 6. However, fault-tolerance cannot be discussed without some prior discussion on system model issues. This is done in this section.

5.1. Synchrony and Timeliness

The synchrony of a system defines the timing assumptions that are made on the behavior of processes and communication channels. More specifically, one usually considers two major parameters. The first parameter is the *process speed interval*, which is given by the difference between the speed of the slowest and the fastest processes in the system. The second parameter is the *communication delay*, which is given by the time elapsed between the sending and the receipt of messages. The synchrony of the system is defined by considering various bounds on these two parameters.

A system where both parameters have a known upper bound is called a *synchronous system*. At the other extreme, a system in which process speed and communication delays are unbounded is called an *asynchronous system*. Between those two extremes lie the definition of various partially synchronous system models [Dolev et al. 1987; Dwork et al. 1988].

A third model that is considered by several total order broadcast algorithms is the *timed asynchronous* model defined by Cristian and Fetzer [1999]. In its most simple form, this model can be seen as an asynchronous model with the notion of physical time and an assumption that "most messages are likely to reach their destination within a known delay δ" [Cristian et al. 1997; Cristian and Fetzer 1999].

5.2. Impossibility Results

There is an important theoretical result related to the consensus problem (see Footnote 10). It has been proven that there is no deterministic solution to the problem of consensus in asynchronous systems if just a single process can crash [Fischer et al. 1985]. Dolev et al. [1987] have shown that total order broadcast can be transformed into consensus, thus proving that the impossibility of consensus also holds for total order broadcast. These impossibility results were the motivation to extend the asynchronous system with the introduction of *oracles* to make consensus and total order broadcast solvable.[11]

5.3. Oracles

In short, a (distributed) oracle can be seen as some component that processes can query. An oracle provides information that algorithms can use to guide their choices. The oracles most frequently considered in distributed systems are failure detectors and coin flips. Since the information provided by these oracles make consensus and total order broadcast solvable, they augment the power of the asynchronous system model.

5.3.1. Failure Detectors. A failure detector is an oracle that provides information about the current status of processes, for instance, whether a given process has crashed or not.

The notion of failure detectors has been formalized by Chandra and Toueg [1996]. Briefly, a failure detector is modeled as a set of distributed modules, one module FD_i attached to each process p_i. Any process p_i can query its failure detector module FD_i about the status of other processes.

Failure detectors may be *unreliable*, in the sense that they provide information that may not always correspond to the real state of the system. For instance, a failure detector module FD_i may provide the erroneous information that some process p_j has crashed while, in reality, p_j is correct and running. Conversely, FD_i may provide the information that a process p_k is correct, while p_k has actually crashed.

To reflect the unreliability of the information provided by failure detectors, we say that a process p_i *suspects* some process p_j whenever FD_i, the failure detector module attached to p_i, returns the (unreliable) information that p_j has crashed. In other words, a suspicion is a belief (e.g., "p_i believes that p_j has crashed") as opposed to a known fact (e.g., "p_j has crashed and p_i knows that").

There exist several classes of failure detectors, depending on how unreliable the information provided by the failure detector can be. Classes are defined by two properties, called *completeness* and *accuracy*, that constrain the range of possible mistakes. In this article, we consider four different classes of failure detectors, called $\mathcal{P}$ (perfect), $\diamond\mathcal{P}$ (eventually perfect), $\mathcal{S}$ (strong), and $\diamond\mathcal{S}$ (eventually strong). The four classes share the same property of completeness, and only differ by their accuracy property [Chandra and Toueg 1996]:

(STRONG COMPLETENESS) Eventually every faulty process is permanently suspected by all correct processes.

(STRONG ACCURACY) No process is suspected before it crashes. [class $\mathcal{P}$]

(EVENTUAL STRONG ACCURACY) There is a time after which correct processes are not suspected by any correct process. [class $\diamond\mathcal{P}$]

[11] Chandra and Toueg [1996] show that consensus can be transformed into total order broadcast. The result holds also for arbitrary failures. So, consensus and total order broadcast are equivalent problems, that is, if there exists an algorithm that solves one problem, then it can be transformed into an algorithm that solves the other problem.

(WEAK ACCURACY) Some process is never suspected. [class $\mathcal{S}$]

(EVENTUAL WEAK ACCURACY) There is a time after which some correct process is never suspected by any correct process. [class $\diamond\mathcal{S}$]

A failure detector of class $\diamond\mathcal{S}$ with a majority of correct processes allows us to solve consensus [Chandra and Toueg 1996]. Moreover, Chandra et al. [1996] have shown that a failure detector of class $\diamond\mathcal{S}$ is the weakest failure detector that allows us to solve consensus.[12]

5.3.2. Random Oracle. Another approach to extend the power of the asynchronous system model is to introduce the ability to generate random values. For instance, processes could have access to a module that generates a random bit when queried (i.e., a Bernoulli random variable).

This approach is used by a class of algorithms called randomized algorithms. These algorithms can solve problems such as consensus (and so total order broadcast) in a probabilistic manner. The probability that such algorithms terminate before some time t, goes to one, as t goes to infinity (e.g., Ben-Or [1983] and Chor and Dwork [1989]). Note that solving a problem deterministically and solving it with probability 1 are not the same.

5.4. Uniformity for Free

In Section 2, we explained the difference between *uniform* and *nonuniform* specifications. Guerraoui [1995] shows that any algorithm that solves Consensus with $\diamond\mathcal{P}$ ($\mathcal{S}$, $\diamond\mathcal{S}$, respectively), also solves Uniform Consensus with $\diamond\mathcal{P}$ ($\mathcal{S}$, $\diamond\mathcal{S}$, respectively).

It is easy to show that this result also holds for total order broadcast. Assume that there exists an algorithm that solves nonuniform total order broadcast (nonuniform Agreement, nonuniform Total Order) with $\diamond\mathcal{P}$, $\mathcal{S}$, or $\diamond\mathcal{S}$, but does not solve uniform total order broadcast. Using the transformation of total order broadcast to consensus (see Section 5.2), this algorithm could be used to obtain an algorithm that solves nonuniform consensus, but not consensus. This is in contradiction to Guerraoui [1995]. Hence, enforcing uniformity has no additional cost in the asynchronous models with $\diamond\mathcal{P}$, $\mathcal{S}$, and $\diamond\mathcal{S}$ failure detectors.

Note however that the result does not hold for total order broadcast algorithms that rely on a perfect ($\mathcal{P}$), or almost perfect failure detector (see Section 5.5).

5.5. Process Controlled Crash

Process controlled crash is the ability given to processes to kill other processes or to commit suicide. In other words, this is the ability to artificially force the crash of a process. Allowing process controlled crash in a system model augments its power. Indeed, this makes it possible to transform severe failures (e.g., omission, Byzantine) into less severe failures (e.g., crash), and to emulate an "almost perfect" failure detector. However, this power does not come without a price.

Automatic transformation of failures. Neiger and Toueg [1990] present a technique that uses process controlled crash to transform severe failures (e.g., omission, Byzantine) into less severe ones (i.e., crash failures). In short, the technique is based on the idea that processes have their behavior monitored. Then, whenever a process begins to behave incorrectly (e.g., omission, Byzantine), it is killed.[13]

However, this technique cannot be used in systems with lossy channels, or those subject to partitions. Indeed, in such contexts, processes might end up killing each other until not a single one is left alive in the system.

Emulation of an almost perfect failure detector. A perfect failure detector ($\mathcal{P}$) satisfies both strong completeness and strong accuracy (no process is suspected before

[12]The weakest failure detector to solve consensus is usually said to be $\diamond\mathcal{W}$, which differs from $\diamond\mathcal{S}$ by satisfying a weak completeness property instead of Strong Completeness. However, Chandra and Toueg [1996] prove the equivalence of $\diamond\mathcal{S}$ and $\diamond\mathcal{W}$.

[13]The actual technique is more complex than what is described here, but this gives the basic idea.

it crashes [Chandra and Toueg 1996]). In practical systems, perfect failure detectors are extremely hard to implement because of the difficulty in distinguishing crashed processes from very slow ones. The idea of the emulation is simple: whenever a failure detector suspects a process p, then p is killed (forced to crash). Fetzer [2003] proposes a different emulation, based on reliable watchdogs, to ensure that no process is suspected before it crashes.

Cost of a free lunch. Process controlled crash has a price. A fault-tolerant algorithm can only tolerate the crash of a bounded number of processes. In a system with process controlled crash, this limit includes not only genuine failures, but also failures provoked through process controlled crash. This means that each provoked failure effectively *decreases* the number of genuine failures that can be tolerated, thus degrading the actual fault-tolerance of the system.

6. MECHANISMS FOR FAULT-TOLERANCE

The total order broadcast algorithms described in Section 4 are not tolerant to failures: if a single process crashes, the properties specified in Section 2.3 are not satisfied. To be fault-tolerant, total order broadcast algorithms rely on various techniques presented in this section. Note that it is difficult to discuss these techniques without getting into specific implementation details. Nevertheless, we try to keep the discussion as general as possible. Notice also that algorithms may actually combine several of these techniques, for example, failure detection (Section 6.1) with resilient communication patterns (Section 6.3).

6.1. Failure Detection

A recurrent pattern in all distributed algorithms is for a process p to wait for a message from some other process q. If q crashes, process p is blocked. Failure detection is one basic mechanism to prevent p from being blocked.

Unreliable failure detection has been formalized by Chandra and Toueg [1996] in terms of two properties: *accuracy* and *completeness* (see Section 5.3.1). Completeness prevents the blocking problem just mentioned. Accuracy prevents algorithms from running forever without solving the problem.

Unreliable failure detectors might be too weak for some total order broadcast algorithms which require *reliable* failure detection information provided by a *perfect* failure detector, known as $\mathcal{P}$ (see Section 5.5).

6.2. Group Membership Service

The low-level failure detection mechanism is not the only way to address the blocking problem mentioned in the previous section. Blocking can also be prevented by relying on a higher-level mechanism, namely a *group membership service*.

A group membership service is a distributed service that is responsible for managing the membership of groups of processes (see Section 3.4 and survey by Chockler, Keidar, and Vitenberg [2001]). The successive memberships of a group are called the *views* of the group. Whenever the membership changes, the service reports change to all group members by providing them with the new view.

A group membership service usually provides strong completeness: if a process p member of some group G crashes, the membership service provides to the surviving members of G a new view from which p is excluded. In the primary-partition model (see Section 3.4), the accuracy of failure notifications is ensured by forcing the crash of processes that have been incorrectly suspected and excluded from the membership, a mechanism called *process-controlled crash* (see Section 5.5).

Moreover in the primary-partition model, the group membership service provides consistent notifications to the group members: the successive views of a group are notified in the *same order* to all of its members.

To summarize, while failure detectors provide inconsistent failure notifications, a group membership service provides

consistent failure notifications. Moreover, total order algorithms that rely on a group membership service for fault-tolerance, exploit another property that is usually provided along with the membership service, namely *view synchrony* (see Section 3.3). Roughly speaking, view synchrony ensures that between two successive views v and v', processes in the intersection $v \cap v'$ deliver the same set of messages. Group membership service and view synchrony have been used to implement complex group communication systems (e.g., Isis [Birman and van Renesse 1994], Totem [Moser et al. 1996], Transis [Dolev and Malkhi 1994, 1996; Amir et al. 1992], Phoenix [Malloth et al. 1995; Malloth 1996]).

6.3. Resilient Communication Patterns

As shown in the previous sections, an algorithm can rely on a failure detection mechanism, or on a group membership service, to avoid the blocking problem. To be fault-tolerant, another solution is to avoid any potential blocking pattern.

Consider, for example, a process p waiting for $n-f$ messages, where n is the number of processes in the system, and f the maximum number of processes that may crash. If all correct processes send a message to p, then the above pattern is nonblocking. We call such a pattern a *resilient* pattern. If an algorithm uses only resilient patterns, it avoids the blocking problem *without* using any failure detector mechanism or group membership service. Such algorithms have, for instance, been proposed by Rabin [1983], Ben-Or [1983], and Pedone et al. [2002] (the first two are consensus algorithms, see Footnote 10).

6.4. Message Stability

Avoiding blocking is not the only problem that fault-tolerant total order broadcasts algorithms have to address. Figure 1 illustrates a violation of the Uniform Agreement property. Notice that this problem is unrelated to blocking.

The mechanism that solves the problem is called *message stability*. A message m is said to be *k-stable*, if m has been received by k processes. In a system in which at most f processes may crash, $f+1$-stability is the important property to detect. If some message m is $f+1$-stable, then m is received by at least one correct process. With such a guarantee, an algorithm can easily ensure that m is eventually received by all correct processes. $f+1$-stability is often simply called *stability*. The detection of stability is generally based on some acknowledgment scheme or token passing.

Another use for message stability is the reclaiming of resources. Indeed, when a process detects that a message has become stable throughout the system, it can release resources associated with that message.

6.5. Consensus

The mechanisms described so far are low-level mechanisms on which fault-tolerant total broadcast algorithms may rely.

Another option for a fault-tolerant total order broadcast algorithm is to rely on higher-level mechanisms that solve all the problems related to fault-tolerance (i.e., the problems previously mentioned). The consensus problem (see Footnote 10) is such a mechanism. Some algorithms solve total order broadcast by reducing it to a consensus problem. This way, fault-tolerance, including failure detection and message stability detection, is hidden within the consensus abstraction.

6.6. Mechanisms for Lossy Channels

Apart from the mechanisms used to tolerate process crashes, we need to say a few words about mechanisms to tolerate channel failures. First, it should be mentioned that several total order broadcast algorithms avoid the issue by relying on some communication layer that takes care of message loss (i.e., these algorithms assume reliable channels, and hence do not discuss message loss). In contrast, other algorithms are built directly on top of lossy channels, and so address message loss explicitly.

To address message loss, the standard solution is to rely on a positive or a negative acknowledgment mechanism. With positive acknowledgment, the receipt of messages is acknowledged; with negative acknowledgment, the detection of a missing message is signaled. The two schemes can be combined.

Token-based algorithms (i.e., moving sequencer or privilege-based algorithms) rely on token passing to detect message losses: the token can be used to convey acknowledgments, or to detect missing messages. So token-based algorithms use the token for ordering purpose, but also for implementing reliable channels.

Table II. Abbreviations Used in Tables III–V

○	*yes*	
△	*somewhat*	explained in the text
×	*no*	
spec.	*special*	explained in the text
inf.	*informal*	explained in the text
NS	*not specified*	means also "not discussed"
n/a	*not applicable*	
+a	*positive acknowledgment*	
−a	*negative acknowledgment*	
GM	*group membership*	
FD	*failure detector/detection*	
Cons.	*consensus*	
RCP	*resilient communication patterns*	
ByzA.	*Byzantine agreement*	

7. SURVEY OF EXISTING ALGORITHMS

This section provides an extensive survey of total order broadcast algorithms. We present about sixty algorithms published in scientific journals or conference proceedings over the past three decades. We have made every possible effort to be exhaustive, and we are quite confident that this article presents a good picture of the field at the time of writing. However, because of the continuous flow of papers on the subject, we might have overlooked one algorithm or two.

In Tables III–V, we present a condensed overview of all surveyed algorithms, in which we summarize the important characteristics of each algorithm. The Tables present only factual information about the algorithms as it appears in the relevant papers. In particular, the Tables do not present information that is the result of extrapolation, or nonobvious deduction; the exception is when we had to interpret information to overcome differences in terminology. Also, properties that are discussed in the original paper, yet not proved correct, are reported as "informal" in the Tables. For the sake of conciseness, several symbols and abbreviations have been used throughout the Tables. They are explained in Table II. For each algorithm, Tables III–V provide the following information:

(1) *General information*, that is, the ordering mechanism (see Section 4), and whether the mechanism is time-based or not (Section 4.6).

(2) The *General information* rows are followed by rows describing the assumptions upon which the algorithm is based, that is, what is *provided* to it:

(a) The *System model* rows specify the synchrony assumptions, the assumptions made about process failures (rows: *crash, omission, Byzantine*), and communication channels (rows: *reliable, FIFO*). Reliable channels guarantee that if a correct process p sends a message m to a correct process q, then q will eventually receive m [Aguilera et al. 1999]. The row *partitionable* indicates whether or not the algorithm works with partitionable membership semantics (see Section 3.4). In particular, algorithms in which only processes in a primary partition can work are not considered partitionable.

(b) The rows called *Condition for liveness* discuss the assumptions necessary to ensure the liveness of the algorithm:

—The row *live...X* means that the liveness of the algorithm requires the liveness of the building block X (on which the algorithm relies). For example, *live...GM* means that the algorithm is live, if the group membership building block on which the algorithm relies, is itself live.

Table III. Overview of Total Order Broadcast Algorithms (Part I)

Algorithm	Amoeba §7.1.1	MTP §7.1.2	Tandem §7.1.3	Garcia-M. Spauster §7.1.4	Jia §7.1.5	Isis (seq.) §7.1.6	Navarat. et al. §7.1.7	Phoenix §7.1.8	Rampart §7.1.9	Chang Maxem. §7.2.1	RMP §7.2.2	DTP §7.2.3	Pin-wheel §7.2.4	On-demand §7.3.1	Train §7.3.2	Token-FD §7.3.3	Totem §7.3.4	TPM §7.3.5	Gopal Toueg §7.3.6	RTCAST §7.3.7	MARS §7.3.8
Ordering mechanism																					
class	fixed sequencer									moving sequencer				privilege-based							
time-based																					◯
System model																					
synchrony	asynchronous												timed asynchronous	asynchronous					synch. (spec.)	synchronous synch. clocks	
crash	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
omission									◯										◯		
Byzantine									◯												
partitionable																	◯				
reliable						◯	◯	◯	◯					◯					◯		◯
FIFO				◯	◯	◯			◯										◯	◯	
Condition needed for liveness																					
live ...						GM		GM				GM									
other	NS	△	NS	recovery			NS		NS	NS	NS		NS	NS	NS	spec.	NS	NS	n/a	n/a	n/a
Building blocks																					
view sync.						◯		◯	◯												
reliable b.																					
causal b.						◯															
consensus																					
other																					
Properties ensured																					
Agreement	inf.	inf.	inf.	◯	NS	inf.	inf.	◯	◯	inf.	inf.	inf.	◯	inf.	inf.	◯	◯	◯	◯	◯	NS
Unif. A				×	NS			◯/×	◯				×			◯	◯/×	◯	◯	◯	NS
Total Order	inf.	◯	inf.	◯	◯	inf.	inf.	◯	◯	inf.	inf.	◯	inf.	inf.	inf.	◯	◯	◯	◯	◯	NS
Unif. TO		×		×	×			◯/×	◯			◯				◯	◯/×	◯	◯	◯	NS
FIFO order					△	◯					◯						◯				
causal ord.					△	◯					◯						◯				
Destination groups																					
multiple				◯	◯													△			
open											◯										
Fault tolerance mechanism																					
process	GM	spec.	GM	block.	GM	GM	GM	GM	GM	GM	GM	GM	GM	GM	GM	FD	GM	GM	Cons.	GM	GM
comm.	+a,−a	−a	+a	−a	−a	n/a	n/a	n/a	n/a	+a,−a	+a,−a	+a,−a	−a	+a,−a	GM	n/a	−a	+a,−a	n/a	GM	n/a

Table IV. Overview of Total Order Broadcast Algorithms (Part II)

Algorithm	Lamport §7.4.1	Psync §7.4.2	Newtop (sym.) §7.4.3	Ng §7.4.4	ToTo §7.4.5	Total §7.4.6	ATOP §7.4.7	COReL §7.4.8	Determ. merge §7.4.9	HAS §7.4.10	Redund. chan. §7.4.11	Quick-S §7.4.12	ABP §7.4.13	Atom §7.4.14	QoS preserv. §7.4.15	Newtop (asym.) §7.6.1	Hybrid §7.6.2	Indulg. unif. TO §7.6.3	Opt. TO in WAN §7.6.4
Ordering mechanism																			
class	communication history															hybrid			
time-based									○	○	○	○							○
System model																			
synchrony	asynchronous								synchronous sync. clocks			spec.	sync.	synchronous sync. clocks		asynchronous			
crash		○	○	○	○	○	○	○		○	○	○	○	○	○	○	○	○	○
omission						○/×				○		○							
Byzantine						○/×				○/×		○							
partitionable			○		○	○	○	○								○			
reliable	○		○	○	○		○	○	○			n/a		○	○	○	○	○	○
FIFO	○		○				○		○			n/a		○	○	○	○		
Condition needed for liveness																			
live ...							GM											Cons.	
other	NS		NS	NS	NS	NS		spec.		n/a	n/a	n/a	n/a	n/a	n/a	NS	NS		NS
Building blocks																			
view sync.			○		○		○	○								○	○		
reliable b.																		○	○
causal b.					○														
consensus														△				○	
other								spec.				ByzA.							
Properties ensured																			
Agreement	inf.	△	○	○	○	△	×	○	○	○	○	○	○	○	×	○	inf.	○	inf.
Unif. A	n/a	△	×	○	○/×	n/a	n/a	○	n/a	×	×	○/×	○	○	n/a	×		○	
Total Order	inf.	inf.	○	inf.	○	○	inf.	○	○	○	○	○	○	○	○	○	inf.	○	inf.
Unif. TO	n/a		×		○/×	○		○	n/a	×	×	○/×	×	○	×	×		○	
FIFO order	○	○	○		○			○						○		○			
causal ord.	○	○	○		○			○								○			
Destination groups																			
multiple			○						○							○			
open																			
Fault tolerance mechanism																			
process	n/a	FD	GM	FD	GM	RCP	GM	GM	n/a	RCP	RCP	ByzA.	GM	GM	GM	GM	GM	Cons.	NS
comm.	n/a	+a	n/a	n/a	n/a	+a,−a	n/a	n/a	n/a	flood.	spec.	n/a	+a	n/a	n/a	n/a	n/a	n/a	n/a

Table V. Overview of Total Order Broadcast Algorithms (Part III).

Algorithm	Skeen §7.5.1	Luan Gligor §7.5.2	Le Lann Bres §7.5.3	Chandra Toueg §7.5.4	Rodrigues Raynal §7.5.5	ATR §7.5.6	Scal-atom §7.5.7	Fritzke et al. §7.5.8	optim. ABcast §7.5.9	prefix agreem. §7.5.10	generic bcast §7.5.11	thrifty generic §7.5.12	weak order. §7.5.13	Quick-A §7.5.14	AMp xAMp §7.5.15
General															
class	destinations agreement														
time-based															
System model															
synchrony	asynchronous														sync.
crash	○	○	○	○	spec.	○	○	○	○	○	○	○	○	○	○
omission			○											○	
Byzantine														○	
partitionable															
reliable	○			○		○	○	○	○	○	○	○	○	n/a	○
FIFO						○			○					n/a	
Condition needed for liveness															
live ...				Cons.	Cons.		Cons.	Cons.	Cons.	Cons.	Cons.			ByzA.	
other	NS	NS	NS			$\diamond\mathcal{P}$						△	△		spec.
Building blocks															
view sync.															
reliable b.				○			○	○	○	○	○	○			
causal b.															
consensus				○	○		○	○	○		○			○	
other										spec.		spec.	spec.	ByzA.	
Properties ensured															
Agreement	inf.	inf.	×	○	○	○	○	○	○	○	○	○	○	○	○
Unif. A			n/a	×	○	○	○	○	×	○	○	○	○	○/×	○
Total Order	inf.	inf.	○	○	○	○	○	○	○	○	○	○	○	○	○
Unif. TO			×	×	○	○	○	○	×	○	○	○	○	○/×	×
FIFO order												○			○
causal ord.												○			○
Destination groups															
multiple	○						○	○							
open	○						○								
Fault tolerance mechanism															
process	GM	FD	RCP	Cons.	Cons.	GM	Cons.	Cons.	Cons.	Cons.	Cons.	n/a	RCP	Cons.	GM
comm.	n/a	−a	RCP	n/a	gossip.	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

—The row *other* adds the following information: *NS* = *not specified* means that liveness is not discussed in the article; *n/a* = *not applicable* means that no additional assumption is needed to ensure liveness (this applies mostly to algorithms that assume a synchronous model); △ = *somewhat* and *spec.* = *special* refers to a discussion of liveness later in the article; *recovery* means that the algorithm is blocking, that is, liveness requires the recovery of crashed processes; $\diamond\mathcal{P}/\diamond\mathcal{S}$ refers to the failure detector needed to ensure liveness.

(c) The next group of rows indicate the *building block(s)* used by the algorithm. The building blocks considered are: *view synchrony* (Section 6.2), which encompasses a *group membership* service; *reliable broadcast* (Section 2.3) *causal broadcast* (Section 2.6.2); *consensus* (Section 4.5); or *other*. *Other* can be either ByzA. = *Byzantine agreement*[14] or spec.=*special*, which means that the explanation is in the text.

(3) After discussing what is provided *"to"* the algorithms, we discuss what is provided *"by"* the algorithms.

(a) The first rows give the *Properties ensured* by the algorithms. As discussed in Section 2, total order broadcast is specified by the following properties: Validity, Uniform Agreement, Uniform Integrity, Uniform Total Order. Validity and Uniform Integrity do not appear in the Tables. The reason is that these properties are rarely discussed in the papers (authors usually assume they are trivially ensured).

We first discuss Agreement and Uniform Agreement, then Total Order and Uniform Total Order. Finally, we mention whether the algorithm additionally ensures FIFO order or causal order. In all these entries, one would expect either a *yes* or a *no*. Unfortunately, many papers do not provide proofs (often only informal arguments), which means that these properties can be questioned. In this case, *inf.* = *informal* appears in the Table. If an algorithm does not discuss the properties of total order broadcast at all, the corresponding entry mentions *NS* = *not specified*. If the nonuniform property is only discussed informally, then the corresponding entry for the uniform property is left empty (in an informal discussion, the distinction between the uniform and the nonuniform property usually does not appear). ◯/× (=*yes*/*no*) appears in some entries for the uniform property, meaning that these algorithms provide several levels of Quality of Service (QoS), which include a uniform and a nonuniform version of the algorithm, where the nonuniform version is more efficient. Moreover, for being able to compare nonpartitionable algorithms with partitionable algorithms, we consider the properties enforced by the former, when executed in a nonpartitionable system model.

For the rows *FIFO order* and *causal order*, ◯ = *yes* appears only if this characteristic is explicit in the paper. Otherwise the entry is simply left blank. Finally, if an algorithm is not fault-tolerant, then the distinction between the uniform and the nonuniform properties does not make sense. In this case, the entry mentions *n/a* = *not applicable*.

(b) The rows called *destination groups* indicate whether the algorithm supports the total order broadcast of a message to multiple groups (row *multiple*), and whether the algorithms support *open*

[14]In the Byzantine agreement problem, also commonly known as the "Byzantine generals problem" [Lamport et al. 1982], every process has an *a priori* knowledge that a particular process *s* is supposed to broadcast a single message *m*. Informally, the problem requires that all correct processes deliver the same message, which must be *m*, if the sender *s* is correct. As the name indicates, Byzantine agreement has mostly been studied in relation to Byzantine failures.

groups (see Section 3). The entry is left blank if the issue is not discussed explicitly in the paper.

(4) The last group of rows, called *fault-tolerant mechanisms*, discusses the mechanisms used to provide fault-tolerance. The row *process* mentions the mechanisms used to tolerate process crashes (see Section 6). Note that some of these fault-tolerant mechanisms also appear as *building blocks*. However, not all building blocks have been reported as fault-tolerant mechanisms (e.g., reliable broadcast, causal broadcast).[15]

The row *comm.* mentions the mechanisms used to address message losses. Most of the algorithms assume underlying reliable channels, in which case the entry mentions $n/a = not\ applicable$. The acronyms $+a$ and $-a$ indicate a positive, respectively negative, acknowledgment mechanism. The other entries are *flood* (flooding), *special* (explanation in the text below), and GM = *group membership*. In the context of unreliable channels, the GM mechanism is used in the case were some process p waits for a message from some other process q and if no message is received (e.g., due to loss), then p requests the exclusion of q from the membership.

In Sections 7.1 through 7.6, we give a brief description of each individual algorithm to complement the information provided in the Tables. Unlike the Tables, the text descriptions also present information that we have deduced from the relevant papers. In some cases, the lack of technical details about the algorithms (in particular, in the case of failures) leads us to *extrapolate* their behavior. In this case, we have attempted to avoid being too assertive (by, e.g., using the conditional) and kindly recommend that the reader treat this speculative information with an appropriate degree of skepticism.

[15]The decision of what is a fault-tolerance mechanism, and what is not is somewhat arbitrary. We have decided to keep the number of mechanisms mentioned in Section 6 low, that is, to mention only key mechanisms.

We think that it is useful to stress again the respective roles of the Tables and the accompanying text in Sections 7.1 to 7.6. The Tables provide *factual* information about each algorithm, as it was published in the relevant papers. In contrast, the text provides complementary information, including information that we have *extrapolated*. In particular, the text explains the originality of each algorithm, and complements items that are left vague in the Tables (i.e., these points are vague in the paper itself). Specifically, for some of the algorithms, the properties reported in the Tables are weaker than those the algorithm might ensure. In such a case, the text mentions (and discusses) the stronger property that might hold. We emphasize this point, as misunderstanding the respective roles of text and Tables might lead to the erroneous impression that the text and the Tables are in contradiction.

7.1. Fixed Sequencer Algorithms

Regardless of the variant they adopt (see Section 4.1), all sequencer algorithms assume an asynchronous system model and use time-free ordering. They tolerate crash failures, except for Rampart, which also tolerates Byzantine failures. They all rely on process-controlled crash to cope with failure; either explicitly (e.g., Tandem), or through group membership and exclusion (e.g., Isis, Rampart).

7.1.1. Amoeba. The Amoeba [Kaashoek and Tanenbaum 1996] group communication system supports algorithms of the first two variants of fixed sequencer algorithms. The first one corresponds to the variant UB (unicast-broadcast) illustrated in Figure 6(a) (Section 4.1). The second variant corresponds to BB (broadcast-broadcast), see Figure 6(b). The two variants share the same properties.

Amoeba assumes lossy channels and implements message retransmission as part of the total order broadcast algorithm. Amoeba uses a combination of positive and negative acknowledgments. The

actual protocol is quite complex because it is combined with flow control, and also tries to minimize the communication cost. Amoeba tolerates failures using a group membership service. Suspected processes are excluded from the group as the result of the unilateral decision of a single process.

The properties of the Amoeba algorithms are only discussed informally in the paper. However, since messages are delivered before they are stable, the algorithm can only satisfy the nonuniform properties of Agreement and Total Order.

7.1.2. MTP. MTP [Armstrong et al. 1992] is an algorithm primarily designed for video streaming and similar multimedia applications. The algorithm assumes that the system is not uniform with respect to the probability of process failures. In particular, it assumes that a process, called the master process, never fails. The master is then designated as the sequencer, and the protocols follow variant UUB (unicast-unicast-broadcast, see Figure (c) 6). When a process p has a message m to broadcast, p requests a sequence number for m from the sequencer. Once it has obtained the sequence number, it sends m, together with the sequence number, to all destinations and the master. At the same time, destination processes learn about the status of previous messages and deliver those that have been accepted by the master.

The protocol tolerates crash failures of destination processes and senders, since all parts involving decisions are executed by the master. The failure of the master is briefly discussed at the end of the paper. The authors suggest that the master could be rendered more resilient by introducing redundancy and using replication techniques.

7.1.3. Tandem. The Tandem global update protocol [Carr 1985] is a fixed sequencer algorithm of variant UUB (see Figure 6(c)). The algorithm allows, at most, one application message to be broadcast at a time, and thus does not need sequence numbers. Later, Cristian et al. [1994] describe a variant UB of Tandem that allows concurrent broadcasts (and thus needs sequence numbers).

7.1.4. Garcia-Molina and Spauster. The algorithm proposed by Garcia-Molina and Spauster [1991] is based on a propagation graph (a forest) to support multiple overlapping groups. The propagation graph is constructed is such a way that each group is assigned a starting node. Senders send their messages to the corresponding starting nodes and messages travel along the edges of the propagation graph. Ordering decisions are resolved along the path. When used in a single group setting, the algorithm behaves like other fixed sequencer algorithms (i.e., the propagation graph is a tree of depth 1).

The algorithm assumes an asynchronous model and requires synchronized clocks. However, synchronized clocks are only needed to yield bounds on the behavior of the algorithm when crash failures occur. Neither the ordering mechanism nor the fault-tolerance mechanism actually need them.

In the event of failures, the algorithm behaves in an unconventional manner. Indeed, if a nonleaf process p crashes, then its descendants in the propagation graph do not receive any message until p has recovered. Hence, the algorithm tolerates process crashes only if those processes are guaranteed to eventually recover.

7.1.5. Jia. Jia [1995] proposed another algorithm based on propagation graphs, which creates simpler graphs than the algorithm of Garcia-Molina and Spauster [1991] (see Section 7.1.4). Unfortunately, the algorithm originally proposed by Jia [1995] is incorrect. Chiu and Hsiao [1998] provide a correction to the algorithm which works only in a more restricted model (i.e., only for closed groups). Also, Shieh and Ho [1997] provide a correction to the message complexity calculated by Jia [1995].

Jia's algorithm relies on the notion of meta-groups, defined in the paper as "the set of processes which have exactly the same group memberships" (i.e., the set of processes which belong to the exact same set of destination groups). The meta-groups are organized into propagation trees, according to the membership they represent. The flow of messages is streamlined down the trees, thus creating the delivery order.

Jia [1995] describes a form of group membership mechanism that is used to redefine the parts of the propagation graph that must change when a process is deleted. Jia also suggests that, unlike Garcia-Molina and Spauster's algorithm [1991] (Section 7.1.4), the nodes in the tree consist of entire meta-groups, rather than single processes. Thus, messages would not be stopped unless all members in an intermediary meta-group fail. The issue is, however, only addressed informally.

7.1.6. Isis (Sequencer). Birman et al. [1991] describe several broadcast primitives of the Isis system, including a total order broadcast primitive called ABCAST. The ABCAST primitive is implemented using a fixed sequencer algorithm (different from the algorithm used in earlier versions of the system; see Section 7.5.1). The Isis (sequencer) algorithm is a fixed sequencer algorithm of variant BB (see Figure 6 (b)), which uses a causal broadcast primitive. The algorithm assumes crash failures.

Constructed over a causal broadcast primitive, the Isis ABCAST algorithm preserves causal order. Moreover, although the algorithm does not support total order for multiple overlapping groups, causal order is nevertheless preserved in this context. The total order broadcast algorithm ensures only the nonuniform properties of Agreement and Total Order.

For fault-tolerance, the total order broadcast algorithm relies on a group membership service and view synchrony (Section 6.2).

Finally, the authors also briefly mention that moving the role of the sequencer in the absence of failures might be a way to avoid a bottleneck. However, the idea is not developed further.

7.1.7. Navaratnam et al.. Navaratnam et al. [1988] propose a fixed sequencer protocol of variant UB (see Figure 6(a)).

The fault-tolerance of the algorithm relies on a group membership service and the ability to exclude wrongly suspected processes. Similar to Amoeba (Section 7.1.1), the decision to exclude a suspected process can be taken unilaterally by one single process.

The properties of this algorithm are discussed informally, and it is easy to see that it satisfies the nonuniform properties of Agreement and Total Order. The authors also make a brief remark suggesting that the algorithm does not guarantee uniform properties, but the wording is a little ambiguous and the information provided in the paper is not sufficient to verify this interpretation.

7.1.8. Phoenix. Phoenix [Wilhelm and Schiper 1995] consists of three algorithms which provide different levels of guarantees. The first algorithm (weak order) only guarantees Total Order and Agreement. The second algorithm (strong order) guarantees both Uniform Total Order and Uniform Agreement. Then, the third algorithm (hybrid order) combines both guarantees on a per-message basis.

The three algorithms are based on a group membership service and view synchrony (see Section 3.3).

7.1.9. Rampart. Unlike other sequencer algorithms, which only assume crash failures, the algorithm of Rampart [Reiter 1994, 1996] is designed to tolerate Byzantine failures. This sets this algorithm somewhat apart from the other sequencer algorithms.

Rampart assumes an asynchronous system model with reliable FIFO channels, and a public key infrastructure in which every process initially knows the

public key of every other process. In addition, communication channels are assumed to be authenticated, so that the integrity of messages between two honest (i.e., non-Byzantine) processes is always guaranteed.

Unlike most early work on Byzantine failures, Rampart treats honest and Byzantine processes separately. In particular, the paper defines uniformity as a property that applies to honest processes only (see Note 1 in Section 2.4). With this definition, Rampart satisfies both Uniform Agreement and Uniform Total Order.

The algorithm is based on a group membership service, which requires that at least one third of all processes in the current view reach an agreement on the exclusion of some process from the group. This condition is necessary because Byzantine processes could otherwise purposely exclude correct processes from the group.

7.2. Moving Sequencer Algorithms

We describe here four moving sequencer algorithms, all of which are time-free. To the best of our knowledge, there is no time-based moving sequencer algorithm. It is actually questionable whether time-based ordering would even make sense for algorithms of this class.

The four algorithms behave in a very similar fashion. Actually, three of them—Pinwheel (Section 7.2.4), RMP (Section 7.2.2), and DTP (Section 7.2.3)—are based on the fourth—Chang and Maxemchuck's algorithm [1984] (Section 7.2.1)—which they each improve in a different way. Pinwheel is optimized for a uniform message arrival pattern, RMP provides various levels of guarantees, and DTP provides a faster detection of message stability. The four algorithms also handle process failures very similarly, using a reformation algorithm (see Section 7.2.1). Except for DTP (Section 7.2.4), all algorithms rely on a logical ring along which the token circulates.

The four algorithms tolerate message loss by relying on a message retransmission protocol that combines positive and negative acknowledgments. More precisely, the token carries positive acknowledgments, but when a process detects that a message is missing, it sends a negative acknowledgment to the token site. The negative acknowledgment scheme is used for message retransmission, while the positive scheme is used to detect message stability.

7.2.1. Chang and Maxemchuck. The algorithm proposed by Chang and Maxemchuk [1984] is based on the existence of a logical ring along which a token is passed. The process that holds the token, also known as the token site, is responsible for sequencing the messages that it receives. The passing of the token simultaneously serves two purposes: (1) the transmission of the sequencer role, and (2) the detection of message stability. Point (2) requires that the logical ring spans all destination processes. This requirement is, however, not necessary for ordering messages (point (1)), and hence the algorithm qualifies as a sequencer-based algorithm according to our classification.

When a process failure is detected (perhaps wrongly) or when a process recovers, the algorithm goes through a reformation phase. The reformation phase redefines the logical ring and elects a new initial token holder. The reformation algorithm can be seen as an ad hoc implementation of a group membership service.

The properties of the total order broadcast algorithm are discussed only informally. Nevertheless, it seems plausible that the algorithm ensures Uniform Total Order and Uniform Agreement.

7.2.2. RMP. RMP [Whetten et al. 1994] differs from the other three algorithms in this group in that it is designed to operate with open groups. Additionally, the authors claim that "RMP provides multiple multicast groups, as opposed to a single broadcast group." However, according to their description, supporting multiple multicast groups is merely a characteristic associated with the group membership service. It is, therefore, dubious that

"multiple groups" is used with the meaning that total order is guaranteed for processes that are at the intersection of two groups (see discussion in Section 3.2).

Depending on the user's choice, RMP satisfies Agreement, Uniform Agreement, or neither of these properties. However, in order to ensure the strong guarantees, RMP must assume that a majority of the processes remain correct and always connected. Also, RMP does not preclude the contamination of the group.

7.2.3. DTP. As mentioned, DTP [Kim and Kim 1997] differs from the other algorithms of this class in that it does not rely on a logical ring for the passing of the token. Instead, DTP follows a heuristic, where the token is always passed to the process seen as the least active. Doing this ensures that messages are acknowledged more quickly when the activity (i.e., broadcasting messages) is not uniformly spread among processes.

7.2.4. Pinwheel. The originality of Pinwheel [Cristian et al. 1997] is that the token circulates among the processes at a speed proportional to the global activity of the sending processes (i.e., broadcasting rate).

Pinwheel assumes that a majority of the processes remains correct and connected at all times (majority group). The algorithm is based on the timed asynchronous model of Cristian and Fetzer [1999]. Although it relies on physical clocks for timeouts, Pinwheel does not need to assume that these clocks are synchronized. Furthermore, the algorithm is time-free, since time is not used for ordering messages.

Pinwheel can ensure Uniform Total Order, given an adequate support from its group membership (not detailed in the paper). Pinwheel only satisfies (nonuniform) Agreement, but the authors argue that the algorithm could easily be modified to satisfy Uniform Agreement [Cristian et al. 1997]. Doing this would only require that destination processes wait until a message is known to be stable before delivering it. The authors claim that the algorithm preserves causal order, but this is valid only under certain restrictions that make the problem trivial to solve.[16]

7.3. Privilege-Based Algorithms

Like moving sequencer algorithms, most privilege-based algorithms are based on a logical ring, and for most of them rely on some kind of group membership or reconfiguration protocol to handle process failures.

7.3.1. On-Demand. The On-demand protocol [Cristian et al. 1997], unlike other privilege-based algorithms, does not rely on a logical ring. Instead, processes with a message to broadcast must obtain the token by issuing a request to the current token holder. As a consequence, the protocol is more efficient if senders send long bursts of messages and such bursts rarely overlap. Also, in contrast to the other algorithms, *all processes* must be aware of the identity of the token holder. So, the passing of the token is done using a broadcast.

The On-demand protocol relies on the same model as the Pinwheel protocol (Section 7.2.4). In other words, it assumes a timed asynchronous system model and physical clocks for timeouts.

A similar algorithm, called Reqtoken, is also described by Friedman and van Renesse [1997].

7.3.2. Train. The Train protocol [Cristian 1991] is inspired by the image of a train that transports messages and circulates among processes. More concretely, a token (a.k.a., the train) moves along a logical ring and carries the messages. When a process gets the token, it receives the new messages carried by the token, acknowledges them, and appends its own messages to the token. Then, it passes the token to the next process. The Train protocol, where messages are carried by the token, is in

[16] In systems with a single closed group, where processes are only allowed to communicate using total order broadcast, causal order is satisfied trivially by simply enforcing FIFO order.

clear contrast to the other algorithms of the same class, where messages are broadcast directly to the destinations. The Train protocol is hence less attractive than the others in a broadcast network.

7.3.3. Token-FD. Ekwall et al. [2004] also present an algorithm based on token-passing in a ring. The algorithm is special because it relies on an unreliable failure detector to tolerate failures, while all other token-based algorithms use a form of group membership.

In the basic version of the algorithm, the token is the only carrier of information, just as in the Train protocol (an optimization is also described, in which the token carries message identifiers). However, the token is sent not only to the immediate successor in the ring, but to $f+1$ successors, where f is the number of crashes that the algorithm tolerates. The additional copies are only used if a process suspects the crash of its predecessor. For its liveness, the algorithm requires a failure detector defined specifically for rings. This failure detector is stronger than $\diamond\mathcal{S}$, but weaker than $\diamond\mathcal{P}$ (see Section 5.3.1).

7.3.4. Totem. The specificity of Totem [Amir et al. 1995] compared to other privilege-based algorithms is that it is designed for partitionable systems. The ordering guarantee ensured is Strong Total Order. Totem provides both *(nonuniform)* agreement and total order (called *agreed order*), and *uniform* agreement and total order (called *safe order*), when operated in a nonpartitionable system. Causal order is also ensured.

The algorithm uses a membership protocol, which has the responsibility for detecting processor failures, network partitioning, and loss of the token. When such failures are detected, the membership protocol reconstructs a new ring, generates a new token, and recovers messages that had not been received by some of the processors when the failure occurred.

The authors observe that, while moving sequencer algorithms (in which holding the token is not required to broadcast a message) have good latency at low loads, latency increases at high loads and in the presence of processor crashes. Moreover, according to Agarwal et al. [1998], the ring and the token-passing scheme make privilege-based algorithms highly efficient in broadcast LANs, but less suited to interconnected LANs. To overcome this problem, they extend Totem to an environment consisting of multiple interconnected LANs. The resulting algorithm performs better in such an environment, but otherwise has the same properties as the original single-ring one.

7.3.5. TPM. TPM [Rajagopalan and McKinley 1989] is closely related to Totem. The main difference is that TPM is not partitionable (it only supports primary partition membership). Moreover, TPM only provides *uniform* agreement and total order. Finally, while TPM only supports a closed group, the authors discuss some ideas on how to extend the algorithm to support multiple closed groups.

Rajagopalan and McKinley [1989] also propose a modification of TPM in which retransmission requests are sent separately from the token in order to improve the behavior in networks with a high rate of message loss.

7.3.6. Gopal and Toueg. Gopal and Toueg's [1989] algorithm is based on the round synchronous model. The round synchronous model is a computation model in which the execution of processes is synchronized according to rounds. During each round, every process performs the same actions: (1) send a message to all processes, (2) receive a message from all noncrashed processes, and then (3) perform some computations.

The algorithm works as follows. For each round, one of the processes is designated as the *transmitter*. The transmitter of some round r is the only process which is allowed to broadcast new application messages in round r. In that round, the other processes broadcast acknowledgments of previous messages. Messages

are delivered once they are acknowledged, three rounds after their initial broadcast.

7.3.7. RTCAST. RTCAST [Abdelzaher et al. 1996] was designed for applications that need real-time guarantees. The algorithm assumes a synchronous system with synchronized clocks. These strong guarantees allow for simplification in the protocol. The paper also shows how the maximum token rotation time can be used for the admission control and schedulability analysis of real-time messages (with the goal to guarantee the delivery deadline of these messages).

7.3.8. MARS. MARS [Kopetz et al. 1991] is based on the technique of *time division multiple-access* (TDMA; see Note 11). TDMA consists of predetermined periodic time slots assigned to each process. Processes are then allowed to send or broadcast messages only during their own time slots. The system assumes that processes have synchronized clocks, whereby they are able to accurately determine the beginning and the end of their own time slot. In addition, communication is assumed to be reliable, and with bounded delays.

Based on the mutual exclusion provided by TDMA and the communication model, total order broadcast is easily implemented. The ordering mechanism can be seen as similar to Gopal and Toueg's algorithm (Section 7.3.6), but in a time-based model, where communication uses time rather than messages [Lamport 1984].

Kopetz et al. [1991] do not discuss the behavior of their total order broadcast algorithm in the presence of failures. This makes it difficult to determine whether the algorithm is uniform or not. We believe that it is not uniform, simply because uniformity induces a cost in performance that the authors are unlikely to consider affordable.

7.4. Communication History Algorithms

7.4.1. Lamport. The principle of Lamport's algorithm [Lamport 1978b], which uses logical clocks, was explained in Section 4.4 (see Figure 11). Actually, the paper describes a mutual exclusion algorithm. However, it is straightforward to derive a total order broadcast algorithm from the mutual exclusion algorithm. Since the delivery order of a message m is determined by the timestamp of the broadcast event of m, the total order is an extension of causal order. The algorithm is not tolerant to failures.

A similar algorithm is described by Attiya and Welch [1994], when comparing consistency criteria.

7.4.2. Psync. The Psync algorithm [Peterson et al. 1989] is used in several group communication systems: Consul [Mishra et al. 1993], Coyote [Bhatti et al. 1998], and Cactus [Hiltunen et al. 1999]. In Psync, processes dynamically build a causality graph of messages they receive. Psync then delivers messages according to a total order that is an extension of the causal order.

Psync assumes an asynchronous system model with (permanent) crash failures and (transient) lossy communication. To tolerate process failures, the algorithm seems to assume a perfect failure detector, although this is not stated explicitly in the paper. To implement reliable channels, the algorithm uses negative acknowledgments (to request the retransmission of lost messages).

Psync is specified only informally. Nevertheless, we believe that the protocol ensures Total Order in the absence of failures. The behavior in the face of failures is unfortunately not described in enough detail to make a confident claim about it. Agreement is a little more complex. In the absence of message loss, Psync ensures Agreement. However, with certain combinations of process crash and message loss, it is possible that some correct processes *discard* messages that are otherwise delivered by others. Hence, when message loss is considered, Agreement can be violated. This problem is discussed in detail by the authors, who relate it to an instance of the "last acknowledgment problem."

Malhis et al. [1996] provide an analysis of the performance of Psync in the presence of message loss. They conclude that Psync performs well if broadcasts are frequent and message loss rare, but performs poorly when broadcasts are infrequent and message loss common. They show that the performance can be improved by regularly sending empty messages, as is done by other communication history algorithms (see Note 14 in Section 4.4).

7.4.3. Newtop (Symmetric). Ezhilchelvan et al. [1995] propose two algorithms: a symmetric one and an asymmetric one. The symmetric algorithm extends Lamport's algorithm (Section 7.4.1) in several ways: it makes it fault-tolerant, allows a process to be member of multiple groups, and allows the broadcast of a message to multiple groups. As for Lamport's algorithm, Newtop preserves causal order.

Newtop is based on a partitionable group membership service (see Section 3.4). The Newtop platform leaves it to applications to decide whether or not they should maintain more than one subgroup in such a situation. Newtop satisfies the property of Weak Total Order mentioned in Section 3.4.

The asymmetric algorithm belongs to a different class, and is hence discussed in the relevant section (Section 7.6.1). The two algorithms (symmetric and asymmetric) can easily be combined to allow the use of the symmetric algorithm in some groups, and the asymmetric algorithm in others.

7.4.4. Ng. Ng [1991] presents a communication history algorithm that uses a minimum-cost spanning tree to propagate messages. The ordering of messages is based on Lamport's clocks, similar to Lamport's algorithm. However, messages and acknowledgments are propagated and gathered, using a minimum-cost spanning tree. The use of a spanning tree improves the scalability of the algorithm and makes it adequate for wide-area networks.

7.4.5. ToTo. The ToTo algorithm [Dolev et al. 1993] ensures Weak Total Order (see Section 3.4; it is called "agreed multicast" in Dolev et al. [1993]). It is built on top of the Transis partitionable group communication system [Dolev and Malkhi 1996]. ToTo extends the order of an underlying causal broadcast algorithm. It is based on dynamically building a causality graph of received messages. The Transis system offers both a uniform and a nonuniform variant of the algorithm. A particularity of ToTo (nonuniform variant) is that, to deliver a message m, a process must have received acknowledgments for m, from as few as a majority of the processes in the current view (instead of all view members).

7.4.6. Total. The Total algorithm [Moser et al. 1993] is built on top of a reliable broadcast algorithm called Trans (Trans is defined together with Total). However, Trans is not used as a black box (which explains why we did not list reliable broadcast as a building block for this algorithm in Table IV). Trans uses an acknowledgment mechanism that defines a partial order on messages. Total extends the partial order of Trans into a total order. Two variants are defined: the more efficient one tolerates $f < n/3$ crashes, and the other tolerates $f < n/2$ crashes.

The Total algorithm fulfills the Agreement property (in fact, Uniform Agreement) with high probability. Actually Total requires the underlying Trans reliable broadcast protocol to provide probabilistic guarantees about not reordering messages. This has some similarities with the notion of *weak ordering oracles* (see Section 7.5.13).

Moser and Melliar-Smith [1999] propose an extension of Total to tolerate Byzantine failures.

7.4.7. ATOP. ATOP [Chockler et al. 1998] is an algorithm following the deterministic merge approach (Section 4.4). The focus of the paper is on adapting the algorithm to different, and possibly changing sending rates. A pseudo-random number

generator is used in computing the delivery order.

The paper is mostly concerned with ensuring an ordering property. This property is Strong Total Order, defined in the context of partitionable systems (Section 3.4). The algorithm ensures FIFO order, and ensures causal order trivially (see Footnote 16).

7.4.8. COReL. The COReL algorithm [Keidar and Dolev 2000] is built on top of a partitionable group membership service like Transis. The underlying service must also offer Strong Total Order (Section 3.4), as well as causal order. COReL gradually builds a global order (Reliable Total Order) by tagging messages according to three different color levels (red, yellow, green). A message starts as red (no knowledge about its position in the global order), then passes to yellow (received and acknowledged when the process is a member of a majority component), and green (all members of the majority component acknowledged the message, and its position in the global order is known). Green messages are delivered to the application. Messages are retransmitted and promoted to green whenever partitions merge. All acknowledgments sent by the algorithm are piggybacked. COReL provides the following liveness guarantee: if eventually there is a stable majority component, all messages sent by the members of this component are delivered.

COReL also supports process recovery if processes are equipped with stable storage. This requires that processes log each message that is sent (before sending the message), and each message that is received (before sending an acknowledgment).

Fekete et al. [2001] formalize a variant of the COReL algorithm and the guarantees offered by the underlying group membership service, using I/O automata.

7.4.9. Deterministic Merge. The main motivation for the deterministic merge algorithm of Aguilera and Strom [2000] is to minimize the expected time that a message is delayed to ensure total order, and to have as few messages as possible sent by destination processes. The algorithm is designed for systems in which several senders send a constant stream of messages (at an approximately fixed rate). In this algorithm, each received message deterministically defines the sender of the next message to be accepted. The algorithm relies on approximately synchronized clocks that are used by senders to put a physical timestamp on their messages. Upon receiving such a timestamped message, a destination process computes (using the timestamp and the sending rates of messages) the next sender from which it will accept a message. The quality of the synchronization is important to ensure good performance of the algorithm, but it is not required for its correctness. The algorithm is most efficient if clocks are synchronized (but works even if they are not) and each sender sends messages at some fixed rate known a priori (the rate may be different for each sender). To ensure the liveness of the algorithm, senders need to send empty messages when they have no message to send (these messages divide the execution into independent *epochs*). The algorithm, as described, is not fault-tolerant.

7.4.10. HAS. Cristian et al. [1995] propose a collection of total order broadcast algorithms (called HAS) that assume a synchronous system model with ϵ-synchronized clocks. The authors describe three algorithms—HAS-$\mathcal{O}$, HAS-$\mathcal{T}$, and HAS-$\mathcal{B}$—that are respectively tolerant to omission failures, timing failures, and Byzantine failures. These algorithms are based on the principle of *information diffusion*, which is itself based on the notion of flooding, or gossiping. In short, when a process wants to broadcast a message m, it timestamps it with the time of emission T, according to its local clock, and sends it to all neighbors. Whenever a process receives m for the first time, it relays it to its neighbors. Processes deliver message m at time $T + \Delta$, according to their local clocks (where Δ is constant that

depends on the topology of the network, the number of failures tolerated, and the maximum clock drift ϵ).

The paper proves that the three HAS algorithms satisfy Agreement. The authors do not prove Total Order, but by the properties of synchronized clocks and the timestamps, Uniform Total Order is not too difficult to enforce. However, if the synchronous assumptions do not hold, the algorithms could violate the safety of the protocol (i.e., Total Order), rather than just its liveness.

7.4.11. Redundant Broadcast Channels. Cristian [1990] presents an adaption of the HAS-$\mathcal{O}$ algorithm (omission failures) to broadcast channels. The system model assumes the availability of $f + 1$ independent broadcast channels (or networks) that connect all processes together, thus creating $f + 1$ independent communication paths between any two processes (where f is the maximum number of failures). Compared to HAS-$\mathcal{O}$, the algorithm for redundant broadcast channels issues significantly fewer messages.

7.4.12. Quick-S. Berman and Bharali [1993] present several closely related total order broadcast algorithms in a variety of system models. In synchronous systems (three variants in the paper), the algorithms are similar to the HAS algorithms: messages are timestamped (with physical or logical timestamps, depending on the system model), and a message, timestamped with T, can be delivered at $T + \Delta$, for some value of Δ. The difference is that they use a Byzantine agreement algorithm with a bounded termination time to send messages. There are algorithms that work with Byzantine failures, and ones that work with crash failures only; the latter ensure Uniform Prefix Order. For Byzantine failures, the algorithm ensures only nonuniform properties. This is because, unlike the *specification* of Rampart (Section 7.1.9), the *specification* used by Quick-S does not distinguish between Byzantine processes and those that only fail by crashing.

The paper also presents an algorithm for asynchronous systems. However, this algorithm belongs to the class of destinations agreement algorithms and is discussed there (Quick-A; Section 7.5.14).

7.4.13. ABP. The principle of ABP [Minet and Anceaume 1991b; Anceaume 1993a] is close to the principle of Lamport's algorithm (Section 7.4.1): messages are delivered according to timestamps attached to messages by their sender. Each process manages a local sequence number variable, used to timestamp messages. Let process p broadcast message m. In the first phase, m and its timestamp value ts_m are sent to all processes. Any process q that receives message m sends back a reply to p. The reply of process q to p may also include some message m', if q had previously broadcast m' with the same timestamp value ($ts_{m'} = ts_m$). Upon reception of all replies from correct processes, process p knows the set $Msg(ts_m)$ of all messages with the same timestamp value ts_m. Process p delivers those messages (ordered according to the identifier of the sender of each message). Process p also broadcasts the set $Msg(ts_m)$, thus allowing the other processes to deliver the same sequence of messages.

7.4.14. Atom. In Atom [Bar-Joseph et al. 2002], streams of messages from all senders are merged in a round-robin fashion. To make the algorithms live, senders need to send empty messages if they have no message to send. This approach can be seen as a special case of *deterministic merge* (see Section 7.4.9).

7.4.15. QoS Preserving Atomic Broadcast. Bar-Joseph et al. [2000] present another algorithm, based on the same ordering mechanism as Atom (Section 7.4.14). As its name indicates, the QoS preserving algorithm provides support for quality of service (QoS), unlike Atom. On the other hand, the QoS preserving algorithm does not guarantee Agreement (i.e., uniform or not), and only nonuniform Total Order.

7.5. Destinations Agreement Algorithms

7.5.1. Skeen. Skeen's algorithm, described by Birman and Joseph [1987], was used in an early version of the Isis toolkit. The algorithm corresponds roughly to the algorithm in Figure 14. The main difference is that Skeen's algorithm computes the global timestamp in a centralized manner, while the algorithm in Figure 14 does it in a decentralized way. Fault-tolerance is achieved using a group membership service, which excludes suspected processes from the group.

Dasser [1992] propose a simple optimization of Skeen's algorithm called TOMP, where additional information is appended to protocol messages in order to deliver application messages a little earlier.

7.5.2. Luan and Gligor. Luan and Gligor [1990] proposed an algorithm based on majority voting. The idea is the following. Upon execution of *TO-broadcast*(m), message m is sent to all processes. Upon reception of m by some process q, m is put into q's receiving buffer. The message delivery order is then decided by a voting protocol, which can be initiated by any of the processes. In case of concurrent initiation of the protocol, an arbitration rule is used.

Voting is initiated by broadcasting an "invitation" message. Consider this message broadcast by process p. Processes reply by sending the content of their receiving buffer to p. Process p waits for a majority of replies. Based on the messages received, process p then constructs a sequence of message identifiers, and broadcasts this sequence. A process receiving the sequence sends an acknowledgment to p. Once p has received acknowledgments from a majority of processes, the proposed sequence is *committed*.

To summarize, the protocol tries to reach consensus among the destination processes on a sequence of messages. However, the authors did not identify consensus as a subproblem to solve, which makes the protocol more complex. The consequence is that the conditions under which liveness is ensured are not discussed (and difficult to infer).

7.5.3. Le Lann and Bres. Le Lann and Bres [1991] wrote a position paper discussing total order broadcast in a system with omission faults. The paper sketches a total order broadcast algorithm based on quorums.

7.5.4. Chandra and Toueg. Chandra and Toueg [1996] propose a transformation of atomic broadcast into a sequence of consensus problems, where each consensus decides on a set of messages, easily transformed into a sequence of messages. The transformation uses reliable broadcast. The idea of this transformation, described in Section 4.5, is not repeated here.

The algorithm assumes an asynchronous system model, reliable broadcast, and a black box that solves consensus. The algorithm is extremely elegant, in the sense that all difficult issues related to fault-tolerance are hidden in the consensus black box.

There have been several proposals to optimize this algorithm. For example, Mostéfaoui and Raynal [2000] propose an optimistic approach in which the consensus algorithm is split into two parts. The first phase is optimized, but does not always succeed. If this happens, the full consensus algorithm is executed.

7.5.5. Rodrigues and Raynal. Rodrigues and Raynal [2000] present a total order broadcast algorithm in a model where processes have access to stable storage and may recover after a crash. The algorithm is very close to the Chandra-Toueg algorithm (Section 7.5.4): it uses the same transformation of total order broadcast to consensus. The only difference is that, because of the crash-recovery model, the algorithm relies on the crash-recovery consensus algorithm of Aguilera, Chen, and Toueg [2000]).

7.5.6. ATR. Delporte-Gallet and Fauconnier [1999] describe the ATR algorithm, which is based on an abstraction

called *Synchronized Phase System (SPS)*. The SPS abstraction is defined in an asynchronous system. An SPS decomposes the execution of an algorithm in rounds, almost like a synchronous round model. The ATR algorithm distinguishes between even and odd rounds. In even rounds, processes send ordered sets of messages to each other. Upon reception of these messages, each process constructs a sequence of messages. In the subsequent odd round, processes try to validate the order and deliver messages.

7.5.7. SCALATOM. SCALATOM Rodrigues et al. [1998] is based on Skeen's algorithm (Section 7.5.1) and supports the broadcast of messages to multiple groups. The algorithm satisfies the Strong Minimality property (Section 3.2.4). The global timestamp is computed using a variant of Chandra and Toueg's [1996] consensus algorithm (Section 7.5.4). SCALATOM corrects an earlier algorithm, called MTO [Guerraoui and Schiper 1997].

7.5.8. Fritzke et al. Fritzke et al. [2001] also propose an algorithm for the broadcast of messages to multiple groups. The algorithm satisfies the Strong Minimality property (Section 3.2.4). Consider a message m broadcast to multiple groups. First, the algorithm uses consensus to decide on the timestamp of m within each destination group. The destination groups then exchange information to compute the final timestamp, and a second consensus is executed in each group to update the logical clock.

7.5.9. Optimistic Atomic Broadcast. Optimism is a technique used for several years in the context of concurrency control [Bernstein et al. 1987] and file system replication [Guy et al. 1993]. However, it has only recently been considered in the context of total order broadcast [Pedone 2001].

The optimistic atomic broadcast algorithm of Pedone and Schiper [1998, 2003] is based on the experimental observation that messages broadcast in a LAN are usually received in the same order by every process. When this assumption is met, the algorithm delivers messages very quickly. However, if the assumption does not hold, the algorithm is less efficient than other algorithms (but still delivers messages in total order).

Unlike most optimistic algorithms, the optimistic atomic broadcast of Pedone and Schiper [2003] is optimistic *internally*. This means that the optimistic mechanism of the algorithm is not apparent to the application. In other words, there is no weakening of the delivery properties.

7.5.10. Prefix Agreement. Anceaume [1997] defines a variant of consensus, called *prefix agreement*, where processes agree on a stream of values, rather than on a single value. Considering streams rather than single values makes the prefix agreement algorithm particularly well suited to solve total order broadcast. The total order broadcast algorithm uses prefix agreement to repeatedly decide on the sequence of messages to be delivered next.

7.5.11. Generic Broadcast. Generic broadcast [Pedone and Schiper 1999; 2002] is not a total order broadcast per se. Instead, the algorithm assumes a *conflict* relation on the messages, and two messages m and m' are delivered in the same order at each destination process, only if they conflict. Two messages m and m' that do not conflict are not ordered by the algorithm. If all messages conflict, then generic broadcast provides the same guarantee as total order broadcast. If no messages conflict, then generic broadcast provides the guarantees of (uniform) reliable broadcast. The strong point of this algorithm is that performance varies according to the required "amount of ordering". The generic broadcast algorithm uses a consensus algorithm only in case of conflicts.

7.5.12. Thrifty Generic Broadcast. Aguilera, Delporte-Gallet et al. [2000] also

propose a generic broadcast algorithm. When conflicting messages are detected, Pedone and Schiper [2002] solve generic broadcast by reduction to consensus, while Aguilera et al. [2000] solve generic broadcast by reduction to total order broadcast. In addition, the algorithm is *thrifty* in the sense that, if there is a time after which broadcast messages do not conflict with each other, then eventually atomic broadcast is no longer used. The algorithm of Pedone and Schiper [2002] also satisfies this property with respect to consensus, but the property was not identified in the paper.

7.5.13. Weak Ordering Oracles. Pedone et al. [2002] define a *weak ordering oracle* as an oracle that orders messages that are broadcast, but is allowed to make mistakes (i.e., the messages broadcast may be delivered out of order). This oracle models the behavior observed in local-area networks, where broadcast messages are often spontaneously delivered in total order. The paper shows that total order broadcast can be solved using a weak ordering oracle. If the optimistic assumption is met, the proposed algorithm, which assumes $f < \frac{n}{3}$, solves total order broadcast in two communication steps.

Interestingly, the algorithm has the same structure as the randomized consensus algorithm proposed by Rabin [1983]. The authors also mention that the weak ordering oracle could be used to design a total order broadcast algorithm with the same structure as the randomized consensus algorithm proposed by Ben-Or [1983].

7.5.14. Quick-A. Berman and Bharali [1993] present a series of four algorithms, three of which belong to another class (see Quick-S, Section 7.4.12). Their algorithm for asynchronous systems is quite different from their algorithms for synchronous systems (Section 7.4.12). Processes maintain a round number, and broadcast messages are timestamped with this round number. The processes then execute a sequence of randomized binary consensus, to decide on the round in which messages are to be delivered.

7.5.15. AMp/xAMp. The AMp [Veríssimo et al. 1989] and xAMp [Rodrigues and Veríssimo 1992] algorithms rely on the assumption that, most of the time, broadcast messages are received by all destination processes in the same order (a realistic assumption in LANs, as already mentioned). So, when a process broadcasts a message, it initiates a commitment protocol. If the messages are received in order by all destination processes, then the outcome is positive: all destination processes commit and deliver the message. Otherwise, the message is rejected and the sender must try again (thus potentially leading to a livelock).

7.6. Hybrid Algorithms

Here we discuss algorithms that do not fit into one of our five classes of total order broadcast algorithms. These algorithms usually combine two different ordering mechanisms.

7.6.1. Newtop (Asymmetric). Ezhilchelvan et al. [1995] propose two algorithms; one symmetric and the other asymmetric. The symmetric algorithm was described earlier (Section 7.4.3).

The asymmetric algorithm uses a sequencer process, and allows a process to be a member of multiple groups (each group has an independent sequencer). For ordering, the algorithm uses Lamport's logical clocks [1978b] in addition to the sequencer. Hence the asymmetric algorithm is a hybrid between a communication history algorithm (due to the use of Lamport's clocks) and a fixed sequencer algorithm. The asymmetric algorithm, like the symmetric one, preserves causal order delivery. However, note that a process p, which is a member of more than one group, cannot broadcast a message m to a group immediately after broadcasting some message m' to a different group. Process p can only deliver m' after it has delivered m. Hence, the asymmetric algorithm does not technically allow a

message to be broadcast to more than one group.

As mentioned in Section 7.4.3, Newtop [Ezhilchelvan et al. 1995] supports the combination of groups, even if one group uses the asymmetric algorithms and the other group uses the symmetric one. Also, Newtop is based on a partitionable group membership service.

7.6.2. Hybrid. Rodrigues et al. [1996] present an algorithm optimized for large networks. The algorithm is hybrid: on a local scale, a sequence number is attached to each message by a fixed sequencer, and on a global scale, the ordering is of type communication history. More precisely, each sender p has an associated sequencer process that issues a sequence number for each message of p. The original message and its sequence number are sent to all, and messages are finally ordered using a standard communication history technique (see Section 7.4.1). The authors also describe interesting heuristics to change the sequencer process. The reasons for such changes can be failures, membership changes, or changes in the traffic pattern.

7.6.3. Indulgent Uniform Total Order. Vicente and Rodrigues [2002] propose an optimistic algorithm for wide-area networks. The algorithm is based on external optimism, as initially proposed by Kemme et al. [1999, 2003]. This means that the algorithm distinguishes between two delivery events following the broadcast of message m: the optimistic delivery, denoted *Opt-deliver(m)*, and the traditional total order delivery, denoted *Adeliver(m)*. Upon *Opt-deliver(m)*, the delivery order of m is not yet decided. However, the application can start processing m. If later, *To-deliver(m)* invalidates the optimistic delivery order, then the application must rollback and undo the processing of m. The optimism of Kemme et al. [2003] is related to the spontaneous total ordering in LANs.

The optimistic algorithm of Vicente and Rodrigues [2002] extends the hybrid algorithm of Rodrigues et al. [1996] (Section 7.6.2). The delivery order is determined by sequence numbers attached to messages. A sequence number attached to a message m must be validated by a majority of processes before the total order of m is decided. Nevertheless, the algorithm optimistically delivers m according to its sequence number before the sequence number is actually validated.

7.6.4. Optimistic Total Order in WANs. Optimistic total order broadcast algorithms rely heavily on the assumption that messages are very often received by all processes in some spontaneous total order. This assumption was motivated by observations made in local networks often over a single hub. The assumption is, however, questionable for wide-area networks, in which the spontaneous total order is significantly less likely to occur. Sousa et al. [2002] propose a time-based solution to address this problem and increase the probability of spontaneous total order in wide-area networks. The technique, called *delay compensation*, consists of artificially delaying received messages, so that all destinations will process them at roughly the same time. A delay is kept for each incoming communication channel, and the duration of this delay is adapted dynamically.

8. OTHER WORK ON TOTAL ORDER AND RELATED ISSUES

Apart from papers proposing total order broadcast algorithms, there is other closely related work that is worth mentioning.

Backoff Protocol. Chockler, Malkhi, and Reiter [2001] describe a replication protocol which emulates *state machine replication* [Lamport 1978a; Schneider 1990]. The protocol is based on quorum systems and relies on a mutual exclusion protocol. Basically, a client process wanting to perform some operation *op* on the replicated servers proceeds as follows: the client first waits to enter the critical section, and then (1) accesses a quorum of replicas to get an up-to-date state σ of the replicated servers, (2) performs the operation *op* on σ which leads to a new state σ',

and (3) updates a quorum of replicas with the new state σ'. The protocol is safe even if the mutual exclusion protocol violates safety (more than one process in the critical section): safety of the mutual exclusion protocol is only needed to ensure progress of the replication protocol.

Optimistic Active Replication. Felber and Schiper [2001] describe another replication protocol that is integrated with a total order broadcast algorithm. The replication protocol is based on an optimistic fixed-sequencer total-order broadcast algorithm, which is executed among the servers. The optimistic algorithm may lead some servers to deliver messages out of order, in which case these servers have to rollback. Rollback is limited to servers; client processes never have to rollback.

Probabilistic Protocols. Recently, Felber and Pedone [2002] have proposed a total ordered broadcast algorithm with probabilistic safety. This means that their algorithms enforce the properties of total order broadcast with a known probability. Doing so makes room for extremely scalable solutions, but it is only acceptable for applications with very weak requirements. In particular, Felber and Pedone [2002] propose a specification where agreement is guaranteed with probability γ_a, total order with probability γ_o, and validity with probability γ_v. The authors propose an algorithm based on gossiping and discuss sufficient conditions under which their algorithm can enforce the above properties with probability one.

Hardware-Based Protocols. Due to their specificity, we have deliberately omitted algorithms that make explicit use of dedicated hardware. However, they deserve to be cited here. Some protocols are based on a modification of the network controllers (e.g., Jalote [1998] and Minet and Anceaume [1991a]). The idea is to slightly modify the network so that it can be used as a virtual sequencer. In our classification system, these protocols can be classified as fixed sequencer protocols. Some other protocols rely on the characteristics of specific networks such as a specific topology [Córdova and Lee 1996], or the ability to reserve buffers [Chen et al. 1996].

Performance of Total Order Broadcast Algorithms. Compared to the host of publications describing algorithms, relatively few papers are concerned with evaluating the performance of total order broadcast (e.g., Cristian et al. [1994], Friedman and van Renesse [1997], Mayer [1992], described in Section 1). Recently, we presented a comparative performance analysis based on the classification developed in this survey [Défago et al. 2003]: algorithms are taken from all five classes of ordering mechanisms, and both uniform and nonuniform algorithms are considered. Urbán et al. [2003] go beyond simply evaluating some algorithm or comparing different algorithms. They propose benchmarks including well-defined performance metrics, workloads, and *faultloads* describing how failures and related events occur.

Formal Methods. Formal methods have been applied both to the problem of total order broadcast, in order to verify the properties of algorithms [Zhou and Hooman 1995; Toinard et al. 1999; Fekete et al. 2001], and to the problem of consensus, in order to construct a truly formal proof for an algorithm [Nestmann et al. 2003]. The proofs of Fekete et al. [2001] were subsequently checked by a theorem prover. Liu et al. [2001] use the notion of meta-properties to describe and analyze a protocol which switches between two total order broadcast algorithms.

Group Communication Controversy. Eleven years ago, Cheriton and Skeen [1993] published a polemic about group communication systems that provide causally and totally ordered communication primitives. Their major argument against group communication systems was that systems based on transactions are more efficient, while providing a stronger consistency model. This was subsequently answered by Birman [1994] and Shrivastava [1994]. More than a decade later, it appears that work on transaction systems and on group communication systems tended to influence each other for a mutual benefit [Schiper

and Raynal 1996; Agrawal et al. 1997; Pedone et al. 1998; Kemme and Alonso 2000; Wiesmann et al. 2000; Kemme et al. 2003].

9. CONCLUSION

The vast literature on total order broadcast and the large number of published algorithms show the complexity of the problem. However, this abundance of information is a problem in itself, because it makes it difficult to understand the exact tradeoffs associated with each proposed solution.

The main contribution of this article is the definition of a classification for total order broadcast algorithms, that makes it easier to understand the relationship between them. It also provides a good basis for comparing the algorithms and understanding some tradeoffs. Furthermore, the article has presented a vast survey of most of the existing algorithms and discussed their respective characteristics.

In spite of the large number of total order broadcast algorithms published, most are merely improvements or variants of each other (even if this is not immediately obvious to the untrained eye). Actually, there are only a few truly original algorithms, but a large collection of various optimizations. Nevertheless, it is important to stress that clever optimizations of existing algorithms often have a very significant impact on performance. For instance, Friedman and van Renesse [1997] show that piggybacking messages, in spite of its simplicity, can significantly improve the performance of algorithms.

Even though the specification of the total order broadcast problem dates back to some of the earliest publications about the subject, few papers actually specify the problem that they solve. In fact, too few algorithms are properly specified, let alone proven correct. Fortunately, this is changing and we hope that this article will contribute to more rigorous work in the future. Without pushing formalism to extremes, a clear specification and a sound proof of correctness are as important as the algorithm itself. Indeed, they clearly define the limits within which the algorithm can be used.

ACKNOWLEDGMENTS

We are grateful to the following people for their helpful advice and constructive criticisms: David E. Bakken, Bernadette Charron-Bost, Adel Cherif, Alan D. Fekete, Takuya Katayama, Tohru Kikuno, Dahlia Malkhi, Keith Marzullo, Rui C. Oliveira, Fernando Pedone, Michel Raynal, Luis T. Rodrigues, Richard D. Schlichting, Tatsuhiro Tsuchiya, and Matthias Wiesmann, as well as Fred B. Schneider, and the anonymous reviewers. We are also thankful to Judith Steeh for proofreading this text.

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Received September 2000; revised August 2003; accepted July 2004