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To cite this version:
Damien Imbs, Achour Mostefaoui, Matthieu Perrin, Michel Raynal. Set-Constrained Delivery Broadcast: Definition, Abstraction Power, and Computability Limits. ICDCN ’18 - 19th International Conference on Distributed Computing and Networking, Jan 2018, Varanasi, India. pp.1-10, 10.1145/3154273.3154296. hal-02053261

HAL Id: hal-02053261
https://hal.archives-ouvertes.fr/hal-02053261
Submitted on 1 Mar 2019

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Set-Constrained Delivery Broadcast: Definition, Abstraction Power, and Computability Limits

Damien Imbs
LIF, Université Aix-Marseille
Marseille, France
damien.imbs@lif.univ-mrs.fr

Matthieu Perrin
LS2N, Université de Nantes
Nantes, France
matthieu.perrin@univ-nantes.fr

Achour Mostéfaoui
LS2N, Université de Nantes
Nantes, France
achour.mostefaoui@univ-nantes.fr

Michel Raynal
Institut Universitaire de France, IRISA, Université de Rennes
Rennes, France
raynal@irisa.fr

ABSTRACT
This paper introduces a new communication abstraction, called Set-Constrained Delivery Broadcast (SCD-broadcast), whose aim is to provide its users with an appropriate abstraction level when they have to implement objects or distributed tasks in an asynchronous message-passing system prone to process crash failures. This abstraction allows each process to broadcast messages and deliver a sequence of sets of messages in such a way that, if a process delivers a set of messages including a message \( m \) and later delivers a set of messages including a message \( m' \), no process delivers first a set of messages including \( m' \) and later a set of message including \( m \).

After having presented an algorithm implementing SCD-broadcast, the paper investigates its programming power and its computability limits. On the “power” side it presents SCD-broadcast-based algorithms, which are both simple and efficient, building objects (such as snapshot and conflict-free replicated data), and distributed tasks. On the “computability limits” side it shows that SCD-broadcast and read/write registers are computationally equivalent.

CCS Concepts

General Terms:
Algorithms, Reliability, Theory

Keywords:
Abstraction, Asynchronous system, Communication abstraction, Conflict-free replicated data type, Design simplicity, Distributed task, Linearity, Message-passing system, Process crash, Read/write atomic register, Snapshot object.

1 INTRODUCTION
Programming abstractions. Informatics is a science of abstractions, and a main difficulty consists in providing users with a “desired level of abstraction and generality” – one that is broad enough to encompass interesting new situations, yet specific enough to address the crucial issues” as expressed in [18]. When considering sequential computing, functional programming and object-oriented programming are well-known examples of what means “desired level of abstraction and generality”.

In the context of asynchronous distributed systems where the computing entities (processes) communicate –at the basic level– by sending and receiving messages through an underlying communication network, and where some of them can experience failures, a main issue consists in finding appropriate communication-oriented abstractions, where the meaning of the term “appropriate” is related to the problems we intend to solve. Solving a problem at the send/receive abstraction level is similar to the writing of a program in a low-level programming language. Programmers must be provided with abstractions that allow them to concentrate on the problem they solve and not on the specific features of the underlying system. This is not new. Since a long time, high level programming languages have proved the benefit of this approach. From a synchronization point of view, this approach is the one promoted in software transactional memory [34], whose aims is to allow programmers to focus on the synchronization needed to solve their problems and not on the way this synchronization must be implemented (see the textbooks [19, 30]).

If we consider specific coordination/cooperation problems, “matchings” between problems and specific communication abstractions are known. One of the most famous examples concerns the consensus problem whose solution rests on the total order broadcast abstraction\(^1\). Another “matching” example is the causal message delivery broadcast abstraction [11, 32], which allows for a very simple implementation of a causal read/write memory [2].

Aim of the paper. The aim of this paper is to introduce and investigate a high level communication abstraction which allows for simple and efficient implementations of concurrent objects and distributed tasks, in the context of asynchronous message-passing systems prone to process crash failures. The concurrent objects in which we are interested are defined by a sequential specification [20] (e.g., a queue). Differently, a task extends to the

\(^1\)Total order broadcast is also called atomic broadcast. Actually, total order broadcast and consensus have been shown to be computationally equivalent [12]. A more general result is presented in [22], where it is introduced a communication abstraction which “captures” the k-set agreement problem [13, 31] (consensus is 1-set agreement).
Content of the paper: a broadcast abstraction. The SCD-broadcast communication abstraction proposed in the paper allows a process to broadcast messages, and to deliver sets of messages (instead of a single message) in such a way that, if a process \( p_i \) delivers a message set \( mset \) containing a message \( m \), and later delivers a message set \( mset' \) containing a message \( m' \), then no process \( p_j \) can deliver first a set containing \( m' \) and later another set containing \( m \). Let us notice that \( p_j \) is not prevented from delivering \( m \) and \( m' \) in the same set. Moreover, SCD-broadcast imposes no constraint on the order in which a process must process the messages it receives in a given message set.

After having defined SCD-broadcast, the paper presents an implementation of it in asynchronous systems where a majority of processes may crash. This assumption is actually a necessary and sufficient condition to cope with the net effect of asynchrony and process failures (see below). Assuming an upper bound \( \Delta \) on message transfer delays, and zero processing time, an invocation of SCD-broadcast is upper bounded by \( 2\Delta \) time units, and \( O(n^2) \) protocol messages (messages generated by the implementation algorithm).

Content of the paper: implementing objects and tasks. Then, the paper addresses two fundamental issues of SCD-broadcast: its abstraction power and its computability limits. As far as its abstraction power is concerned, i.e., its ability and easiness to implement atomic (linearizable) or sequentially consistent concurrent objects [20, 27] and read/write solvable distributed tasks, the paper presents, on the one side, two algorithms implementing atomic objects (namely a snapshot object [1, 3], and a distributed increasing/decreasing counter), and, on the other side, an algorithm solving the lattice agreement task [6, 16].

The two concurrent objects (snapshot and counter) have been chosen because they are encountered in many applications, and are also good representative of the class of objects identified in [4]. The objects of this class are characterized by the fact that each pair \( op_1 \) and \( op_2 \) of their operations either commute (i.e., in any state, executing \( op_1 \) before \( op_2 \) leads to the same state as executing \( op_2 \) before \( op_1 \), as it is the case for a counter), or any of \( op_1 \) and \( op_2 \) can overwrite the other one (e.g., executing \( op_1 \) before \( op_2 \) leads to the same state as executing \( op_2 \) alone). Our implementation of a counter can be adapted for all objects with commutative operations, and our implementation of the snapshot object illustrates how over-writing operations can be obtained directly from the SCD-broadcast abstraction. Concerning these objects, it is also shown that a slight change in the algorithms allows us to obtain implementations (with a smaller cost) in which the consistency condition is weakened from linearizability to sequential consistency [26].

In the case of read/write solvable tasks, SCD-broadcast shows how the concurrency inherent (but hidden) in a task definition can be easily mastered and solved.

Content of the paper: the computability limits of SCD-broadcast. The paper also investigates the computability power of the SCD-broadcast abstraction, namely it shows that SCD-broadcast and atomic read/write registers (or equivalently snapshot objects) have the same computability power in asynchronous systems prone to process crash failures. Everything that can be implemented with atomic read/write registers can be implemented with SCD-broadcast, and vice versa.

As read/write registers (or snapshot objects) can be implemented in asynchronous message-passing system where only a minority of processes may crash [5], it follows that the proposed algorithm implementing SCD-broadcast is resilience-optimal in these systems. From a theoretical point of view, this means that the consensus number of SCD-broadcast is 1 (the weakest possible).

Roadmap. The paper is composed of 8 sections. Section 2 defines the SCD-broadcast abstraction. Section 3 presents a resilience-optimal algorithm implementing SCD-broadcast in asynchronous message-passing systems prone to process crash failures, while Then, Sections 4-6 present SCD-broadcast-based algorithms for concurrent objects and tasks. Section 7 focuses on the computability limits of SCD-broadcast. Finally, Section 8 concludes the paper. Due to page limitations, proofs are not given in the article, but they can be found in [21].

2 THE SCD-BROADCAST COMMUNICATION ABSTRACTION

Process model. The computing model is composed of a set of \( n \) asynchronous sequential processes, denoted \( p_1, ..., p_n \). "Asynchronous" means that each process proceeds at its own speed, which can be arbitrary and always remains unknown to the other processes.

A process may halt prematurely (crash failure), but it executes its local algorithm correctly until it crashes (if it ever does). The model parameter \( t \) denotes the maximal number of processes that may crash in a run \( r \). A process that crashes in a run is said to be faulty in \( r \). Otherwise, it is non-faulty.

Definition of SCD-broadcast. The set-constrained delivery broadcast abstraction (SCD-broadcast) provides the processes with an operation \( \text{scd\_broadcast}(m) \) that takes a message \( m \) to broadcast as parameter, and triggers the event \( \text{scd\_deliver}(mset) \) that provides the process on which it was triggered with a non-empty set of messages \( mset \). Using a classical terminology, when a process invokes the operation \( \text{scd\_broadcast}(m) \), we say that it “scd-broadcasts a message \( m \)”. Similarly, when the event \( \text{scd\_deliver}(mset) \) is triggered on this process, we say that it “scd-delivers the set of messages \( mset \)”. By a slight abuse of language, when we are interested in a message \( m \), we say that a process “scd-delivers the message \( m \)” when actually it scd-delivers the message set \( mset \) containing \( m \).
SCD-broadcast is defined by the following set of properties, where we assume –without loss of generality– that all the messages that are scd-broadcast are different.2

- Validity. If a process scd-delivers a set containing a message \( m \), then \( m \) was scd-broadcast by a process.
- Integrity. A message is scd-delivered at most once by each process.
- MS-Ordering. Let \( p_1 \) be a process that scd-delivers first a message set \( mset_1 \) and later a message set \( mset_1' \). For any pair of messages \( m \in mset_1 \) and \( m' \in mset_1' \), no process \( p_j \) scd-delivers first a message set \( mset_1' \) containing \( m' \) and later a message set \( mset_1 \) containing \( m \).
- Termination-1. If a non-faulty process scd-broadcasts a message \( m \), it terminates its scd-broadcast invocation and scd-delivers a message set containing \( m \).
- Termination-2. If a process scd-delivers a message \( m \), every non-faulty process scd-delivers a message set containing \( m \).

Termination-1 and Termination-2 are classical liveness properties (found for example in Uniform Reliable Broadcast [9, 29]). The other ones are safety properties. Validity and Integrity are classical communication-related properties. The first states that there is neither message creation nor message corruption, while the second states that there is no message duplication.

The MS-Ordering property is new, and characterizes SCD-broadcast. It states that the contents of the sets of messages scd-delivered at any two processes are not totally independent: the sequence of sets scd-delivered at a process \( p_1 \) and the sequence of sets scd-delivered at a process \( p_2 \) may be mutually consistent in the sense that a process \( p_1 \) cannot scd-deliver first \( m \in mset_1 \) and later \( m' \in mset_1' \neq mset_1 \), while another process \( p_j \) scd-delivers first \( m' \in mset_1' \) and later \( m \in mset_1 \neq mset_1' \). Let us nevertheless observe that if \( p_1 \) scd-delivers first \( m \in mset_1 \) and later \( m' \in mset_1' \), \( p_j \) may scd-deliver \( m \) and \( m' \) in the same set of messages.

Let us remark that, if the MS-Ordering property is suppressed and messages are scd-delivered one at a time, SCD-broadcast boils down to the well-known Uniform Reliable Broadcast abstraction [12, 29].

Differently, if all message sets contain exactly one message, SCD-broadcast is equivalent to the Atomic Broadcast abstraction.

**An example.** Let \( m_1, m_2, m_3, m_4, m_5, m_6, m_7 \) and \( m_8 \) be messages that have been scd-broadcast at any two processes. The following scd-deliveries of message sets by \( p_1, p_2 \) and \( p_3 \) respect the definition of SCD-broadcast:

- at \( p_1: \{m_1, m_2\}, \{m_3, m_4, m_5\}, \{m_6\}, \{m_7, m_8\} \).
- at \( p_2: \{m_1\}, \{m_2, m_3\}, \{m_4, m_5, m_6\}, \{m_7\}, \{m_8\} \).
- at \( p_3: \{m_1, m_2, m_3\}, \{m_4, m_5\}, \{m_6, m_7\}, \{m_8\} \).

Differently, due to the scd-deliveries of the sets including \( m_2 \) and \( m_3 \), the following scd-deliveries by \( p_1 \) and \( p_2 \) do not satisfy the MS-broadcast property:

- at \( p_1: \{m_1, m_2\}, \{m_3, m_4, m_5\}, \ldots \)
- at \( p_2: \{m_1, m_3\}, \{m_2\}, \ldots \)

2 The unicity of messages is not restrictive in practice, as one can assume the broadcast operation tags messages with a unique identifier. This way, messages can be unique even if their applicative content is not.

A containment property. Let \( mset^i \) be the \( i \)-th message set scd-delivered by \( p_i \). Hence, at some time, \( p_i \) scd-delivered the sequence of message sets \( mset_1^i, \ldots, mset_n^i \). Let \( MSet^i = mset_1^i \cup \ldots \cup mset_n^i \). The following Containment property follows directly from the MS-Ordering and Termination-2 properties:

\[
\forall i,j,x,y: (MSet_i^x \subseteq MSet_i^y) \lor (MSet_j^y \subseteq MSet_j^x).
\]

**Partial order on messages created by the message sets.** The MS-Ordering and Integrity properties establish a partial order on the set of all the messages, defined as follows. Let \( \rightarrow \) be the local message delivery order at process \( p_i \) defined as follows: \( m \rightarrow m' \) if \( p_i \) scd-delivers the message set containing \( m \) before the message set containing \( m' \). As no message is scd-delivered twice, it is easy to see that \( \rightarrow \) is a partial order (locally know by \( p_i \)). The containment property implies that there is a total order (which remains unknown to the processes) on the whole set of messages, that complies with the partial order \( \rightarrow \leq \) and later. This is where SCD-broadcast can be seen as a weakening of total order broadcast.

3 IMPLEMENTATION OF SCD-BROADCAST

This section shows that the SCD-broadcast communication abstraction is not an oracle-like object (oracles allow us to extend our understanding of computing, but cannot be implemented). It describes an implementation of SCD-broadcast in an asynchronous send/receive message-passing system in which any minority of processes may crash. This system model is denoted \( C\!\!A\!M\!P_{n,t} \) (where \( C\!\!A\!M\!P_{n,t} \) stands for “Crash Asynchronous Message-Passing” and \( t < n/2 \) is its restriction on failures). As \( t < n/2 \) is the weakest assumption on process failures that allows a read/write register to be built on top of an asynchronous message-passing system [5], and SCD-broadcast and read/write registers are computationally equivalent (as shown in Sections 4 and 7), the proposed implementation is optimal from a resilience point of view.

3.1 Underlying communication network

**Send/receive asynchronous network.** Each pair of processes communicate through two uni-directional channels on which they send and receive messages. Hence, the communication network is a complete network: any process \( p_i \) can directly send a message to any process \( p_j \) (including itself). A process \( p_i \) invokes the operation “send \( \text{TYPE}(m) \) to \( p_j \)” to send to \( p_j \) the message \( m \), whose type is \( \text{TYPE} \). The operation “receive \( \text{TYPE}() \) from \( p_j \)” allows \( p_i \) to receive from \( p_j \) a message whose type is \( \text{TYPE} \).

Each channel is reliable (no loss, corruption, nor creation of messages), not necessarily FIFO, and asynchronous (while the transit time of each message is finite, there is no upper bound on message transit times). Let us notice that, due to process and message asynchrony, no process can know if another process crashed or is only very slow.

**Uniform FIFO-broadcast abstraction.** To simplify the presentation, and without loss of generality, we consider that the system is...
equipped with a FIFO-broadcast abstraction. Such an abstraction can be built on top of the previous basic system model without enriching it with additional assumptions (see e.g. [29]). It is defined by the operations fifo_broadcast() and fifo_deliver(), which satisfy the properties of Uniform Reliable Broadcast (Validity, Integrity, Termination 1, and Termination 2), plus the following message ordering property.

- FIFO-Order. For any pair of processes \( p_i \) and \( p_j \), if \( p_i \) fifo-delivers first a message \( m \) and later a message \( m' \), both from \( p_j \), no process fifo-delivers \( m' \) before \( m \).

### 3.2 Algorithm

This section describes Algorithm 1, which implements SCD-\( m \). The algorithm is made up of five fields: the first field is an associated application message generated by Algorithm 1.

**Protocol message.** The algorithm uses a single type of protocol message denoted forward_msg\((m, sd, sn, f, snf)\). Such a message is made up of five fields: the first field is an associated application message \( m \), the second and third form a pair \((sd, sn)\) that is the identity of the application message and the fourth and fifth form a pair \((f, snf)\) that describes the local progress (as captured by \( snf \)) of the forwarder process \( pf \) when it forwarded this protocol message to the other processes by invoking fifo_broadcast forward_msg\((m, sd, sn, f, snf)\) (line 11).

**Operation scd_broadcast().** When \( p_i \) invokes the operation scd_broadcast\((m)\), where \( m \) is an application message, it sends the protocol message forward_msg\((m, i, sn_i, f, snf)\) to itself (this simplifies the writing of the algorithm), and waits until it has no more message from itself pending in buffer\(_i\), which means it has scd-delivered a set containing \( m \) (lines 19 and 20).

**Uniform fifo-broadcast of a message forward_msg.** When a process \( p_i \) fifo-delivers a protocol message forward_msg\((m, sd, sn, f, snf)\), it first invokes the internal operation forward\((m, sd, sn, f, snf)\). In addition to other statements, the first fifo-delivery of such a message by a process \( p_i \) entails its participation in the uniform reliable fifo-broadcast of this message (lines 5 and 11). In addition to the invocation of forward\((m)\), the fifo-delivery of forward_msg\((m)\) invokes also try_deliver\((m)\), which strives to scd-deliver a message set (lines 4).

**The core of the algorithm.** Expressed with the relations \( \Rightarrow_{i} \), \( 1 \leq i \leq n \), introduced in Section 2, the main issue of the algorithm is to ensure that, if there are two messages \( m \) and \( m' \) and a process \( p_i \) such that \( m \Rightarrow_{i} m' \), then there is no \( p_j \) such that \( m' \Rightarrow_{j} m \).

To this end, a process \( p_i \) is allowed to scd-deliver a message \( m \) before a message \( m' \) only if it knows that a majority of processes \( p_j \) have fifo-delivered a protocol message forward_msg\((m, \ldots, \sim, \sim)\) before a protocol message forward_msg\((m', \ldots, \sim, \sim)\). \( p_i \) knows it either (i) because it fifo-delivered from \( p_j \) a message \( \text{forward}_\langle m, \ldots, \sim, \sim \rangle \) before a protocol message \( \text{forward}_\langle m', \ldots, \sim, \sim \rangle \); or (ii) because it fifo-delivered from \( p_j \) both \( \text{forward}_\langle m, \ldots, \sim, \sim, \text{snm} \rangle \) and \( \text{forward}_\langle m', \ldots, \sim, \sim, \text{snm} \rangle \) and the sending date \( \text{snm} \) is smaller than the sending date \( \text{snm}' \). The MS-Ordering property follows then from the impossibility that a majority of processes “sees \( m \) before \( m' \)”, while another majority “sees \( m' \) before \( m \)”.

**Internal operation forward().** This operation can be seen as an enrichment (with the fields \( f \) and \( snf \)) of the reliable fifo-broadcast implemented by the protocol messages forward_msg\((m, sd, sn, f, \ldots)\). Considering such a message forward_msg\((m, sd, sn, f, \ldots)\), \( m \) was scd-broadcast by \( p_{sd} \) at its local time \( sn_{sd} \) and relayed by the forwarding process \( pf \) at its local time \( snf \). If \( sn_{sd} \leq clock_{[sd]} \) then \( p_i \) has already scd-delivered a message set containing \( m \) (see lines 18 and 20). If \( sn_{sd} > clock_{[sd]} \), there are two cases defined by the predicate of line 6.

- No quadruplet \( qdplt \) in \( buffer \) is such that \( qdplt\.msg = m \). In this case, \( p_i \) creates a quadruplet associated with \( m \), and adds it to \( buffer \) (lines 8-10). Then, \( p_i \) participates in the fifo-broadcast of \( m \) (line 11) and records its local progress by increasing \( sn_i \) (line 12).
- There is a quadruplet \( qdplt \) in \( buffer \), associated with \( m \), i.e., \( qdplt = (m, \ldots, \sim, \sim) \in buffer \). In this case, \( p_i \) assigns \( sn_i \) to \( qdplt\.cl[f] \) (line 7), thereby indicating that \( m \) was known and forwarded by \( pf \) at its local time \( snf \).
These quadruplets are withdrawn from buffer entries such that the application messages in the quadruplets of to forward_msg have been seen by a process. Therefore, qdplt is withdrawn from buffer. Then a message set to scd-deliver. This set containing application messages needs to updates sd before scd-delivering a set containing m, when a process is selected by a process. Moreover, when a process invokes write(r, v), where 1 ≤ r ≤ m, by a process p invokes assign atomically v to REG[r]. The invocation of snapshot() returns the value of REG[1..m] as if it was executed instantaneously. Hence, in any execution of a snapshot object, its operations write() and snapshot() are linearizable. The underlying atomic registers can be Single-Reader (SR) or Multi-Reader (MR) and Single-Writer (SR) or Multi-Writer (MW). We consider only SWMR and MWMR registers. If the registers are SWMR the snapshot is called SWMR snapshot (and we have then m = n). Moreover, we always have r = i, when p invokes write(r, v). If the registers are MWMR, the snapshot object is called MWMR.

Implementations based on read/write registers. Implementations of both SWMR and MWMR snapshot objects on top of read/write atomic registers have been proposed (e.g., [1, 3, 23, 24]). The “hardness” to build snapshot objects in read/write systems and associated lower bounds are presented in the survey [15]. The best algorithm known ([7]) to implement an SWMR snapshot requires O(n log n) read/write on the base SWMR registers for both write() and local computation times are equal to zero), each SCD-broadcast costs at most 2Δ time units.

4 SCD-BROADCAST IN ACTION
(ITS POWER): SNAPSHOT OBJECT

4.1 Snapshot object

Definition. A snapshot object is introduced in [1, 3]. A snapshot object is an array REG[1..m] of atomic read/write registers which provides the processes with two operations, denoted write(r, v) and snapshot(). The invocation of write(r, v), where 1 ≤ r ≤ m, by a process p invokes atomically v to REG[r]. The invocation of snapshot() returns the value of REG[1..m] as if it was executed instantaneously. Hence, in any execution of a snapshot object, its operations write() and snapshot() are linearizable.

The underlying atomic registers can be Single-Reader (SR) or Multi-Reader (MR) and Single-Writer (SR) or Multi-Writer (MW). We consider only SWMR and MWMR registers. If the registers are SWMR the snapshot is called SWMR snapshot (and we have then m = n). Moreover, we always have r = i, when p invokes write(r, v). If the registers are MWMR, the snapshot object is called MWMR.

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and snapshot(). As far as MWMR snapshot objects are concerned, there are implementations where each operation has an $O(n)$ cost. As far as the construction of an SNMR (or MWMR) snapshot object in crash-prone asynchronous message-passing systems where $t < \frac{n}{2}$ is concerned, it is possible to stack two constructions: first an algorithm implementing SWMR (or MWMR) atomic read/write registers (e.g., [5]), and, on top of it, an algorithm implementing an SNMR (or MWMR) snapshot object. This stacking approach provides objects whose operation cost is $O(n^2 \log n)$ messages for SWMR snapshot, and $O(n^3)$ messages for MWMR snapshot. An algorithm based on the same low level communication pattern as the one used in [5], which builds an atomic SWMR snapshot object “directly” (i.e., without stacking algorithms) was recently presented in [14] (the aim of this algorithm is to perform better than the stacking approach in concurrency-execution free executions).

4.2 An algorithm for atomic MWMR snapshot in $\text{CAMP}_{n,1}[\text{SCD-broadcast}]$

**Local representation of $\text{REG}$ at a process $p_i$.** At each register $p_i$, $\text{REG}[1..m]$ is represented by three local variables $\text{reg}[1..m]$ (data part), plus $\text{tsa}[1..m]$ and $\text{done}_1$ (control part).

- $\text{done}_i$ is a Boolean variable.
- $\text{reg}[1..m]$ contains the current value of $\text{REG}[1..m]$, as known by $p_i$.
- $\text{tsa}[1..m]$ is an array of timestamps associated with the values stored in $\text{reg}[1..m]$. A timestamp is a pair made of a local clock value and a process identity. Its initial value is $(0, -)$. The fields associated with $\text{tsa}[1]$ are denoted $\langle \text{tsa}[1].r, \text{tsa}[1].date, \text{tsa}[1].\text{proc} \rangle$.

**Timestamp-based order relation.** We consider the classical lexicographical total order relation on timestamps, denoted $<_{ts}$. Let $ts_1 = (h_1, i_1)$ and $ts_2 = (h_2, i_2)$. We have $ts_1 <_{ts} ts_2 \overset{\text{def}}{=} (h_1 < h_2) \lor ((h_1 = h_2) \land (i_1 < i_2))$.

**Algorithm 2: Construction of an MWMR snapshot object $\text{CAMP}_{n,1}[\text{SCD-broadcast}]$ (code for $p_i$)**

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Algorithm 2: Construction of an MWMR snapshot object $\text{CAMP}_{n,1}[\text{SCD-broadcast}]$ (code for $p_i$)
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Algorithm 2: snapshot operation. In this algorithm, a message $\text{SYNC}(i)$ is scd-broadcast (line 1) and after reception of this message (line 12), the local value of $\text{reg}[1..m]$ is returned (line 2). The message $\text{SYNC}(i)$ which is scd-broadcast is a pure synchronization message, whose aim is to entail the refreshment of the value of $\text{reg}[1..m]$ (lines 5-11) which occurs before the setting of $\text{done}_i$ to true (line 12).

Algorithm 2: write operation. (Lines 3-4) When a process $p_i$ wants to assign a value $v$ to $\text{REG}[r]$, it invokes $\text{REG}.\text{write}(r, v)$. This operation starts by a re-synchronization, as in the snapshot operation, whose side effect is here to provide $p_i$ with an up-to-date value of $\text{tsa}[r].\text{date}$ (line 3). Then, $p_i$ associates the timestamp $\langle \text{tsa}[r].\text{date} + 1, i \rangle$ with $v$, and scd-broadcasts the data/control message $\text{write}(r, v, \langle \text{tsa}[r].\text{date} + 1, i \rangle)$. In addition to informing the other processes on its write of $\text{REG}[r]$, this message $\text{write}(\cdot)$ acts as a re-synchronization message, exactly as a message $\text{SYNC}(\cdot)$. When this synchronization terminates (i.e., when the Boolean $\text{done}_i$ is set to true), $p_i$ returns from the write operation.

Algorithm 2: scd-delivery of a set of messages. When process $p_i$ scd-delivers a message set, namely, $\langle \text{write}(r_1, v_{j_1}, \langle \text{date}_{j_1}, i_{j_1} \rangle), \ldots, \text{write}(r_k, v_{j_k}, \langle \text{date}_{j_k}, i_{j_k} \rangle) \rangle$, $\text{sync}(j_{k+1}), \ldots, \text{sync}(j_n) \rangle$ it first looks if there are messages $\text{write}(\cdot)$ if it is the case, for each register $\text{REG}[r]$ for which there are messages $\text{write}(r, v, (\langle \text{tsa}[r].\text{date} + 1, i \rangle))$. Finally, if $p_i$ is the sender of one of these messages ($\text{write}(\cdot)$ or $\text{SYNC}(\cdot)$), $\text{done}_i$ is set to true, which terminates $p_i$’s re-synchronization (line 12).

**Time and Message costs.** An invocation of snapshot() involves one invocation of scd_broadcast(), while an invocation of write() involves two. As scd_broadcast() costs $O(n^2)$ protocol messages and 2A time units, snapshot() cost the same, and write() costs the double.

**Theorem 2.** Algorithm 2 builds an MWMR atomic snapshot object in the model $\text{CAMP}_{n,1}[\text{SCD-broadcast}]$. The operation snapshot costs one SCD-broadcast, the write() operation costs two.
Comparison with other algorithms. Interestingly, Algorithm 2 is more efficient (from both time and message point of views) than the stacking of a read/write snapshot algorithm running on top of a message-passing emulation of a read/write atomic memory (such a stacking would costs \(O(n^2 \log n)\) messages and \(O(n \Delta)\) time units, see Section 4.1).

Sequentially consistent snapshot object. When considering Algorithm 2, let us suppress line 1 and line 3 (i.e., the messages \(\text{SYNC}\) are suppressed). The resulting algorithm implements a sequentially consistent snapshot object. This results from the suppression of the real-time compliance due to the messages \(\text{SYNC}\). The operation \(\text{snapshot}\)() is purely local, hence its cost is 0. The cost of the operation \(\text{write}\)() is one \(\text{SCD-broadcast}\), i.e., \(2\Delta\) time units and \(O(n^2)\) protocol messages. The proof of this algorithm is left to the reader.

5 SCD-BROADCAST IN ACTION (ITS POWER): COUNTER OBJECT

Definition. Let a counter be an object which can be manipulated by three parameterless operations denoted \(\text{increase}\)(), \(\text{decrease}\)(), and \(\text{read}\)(). Let \(C\) be a counter. From a sequential specification point of view \(C.\text{increase}\)() adds 1 to \(C\), \(C.\text{decrease}\)() subtracts 1 from \(C\), \(C.\text{read}\)() returns the value of \(C\). As indicated in the Introduction, due to its commutative operations, this object is a good representative of a class of CRDT objects (conflict-free replicated data type as defined in [33]).

An algorithm satisfying linearizability. Algorithm 3 implements an atomic counter \(C\). Each process manages a local copy of it denoted \(counter_i\). The text of the algorithm is self-explanatory. The operation \(\text{read}\)() is similar to the operation \(\text{snapshot}\)() of the snapshot object. Differently from the \(\text{write}\)() operation on a snapshot object (which requires a synchronization message \(\text{SYNC}\) and a data/synchronization message \(\text{WRITE}\)()), the update operations \(\text{increase}\)() and \(\text{decrease}\)() require only one data/synchronization message \(\text{PLUS}\)() or \(\text{MINUS}\)(). This is the gain obtained from the fact that, from a process \(p_i\) point of view, the operations increase() and decrease() which appear between any consecutive of its read() invocations are commutative.

Theorem 3. Algorithm 3 implements an atomic counter.

An algorithm satisfying sequential consistency. The previous algorithm can be easily modified to obtain a sequentially consistent counter. To this end, a technique similar to the one introduced in [8] can be used to allow the operations increase() and decrease() to have a fast implementation. "Fast" means here that these operations are purely local: they do not require the invoking process to wait in the algorithm implementing them. Differently, the operation \(\text{read}\)() issued by a process \(p_i\) cannot be fast, namely, all the previous \(\text{increase}\)() and \(\text{decrease}\)() operations issued by \(p_i\) must be applied.
to its local copy of the counter for its invocation of read() terminates (this is the rule known under the name "read your writes").

Algorithm 4 is the resulting algorithm. In addition to counter1, each process manages a synchronization counter lsc1 initialized to 0, which counts the number of increase() and decrease() executed by p1 and not yet locally applied to counter1. Only when lsc1 is equal to 0, p1 is allowed to read counter1.

The cost of an operation increase() and decrease() is 0 time units plus the O(n^2) protocol messages of the underlying SCD-broadcast. The time cost of the operation read() by a process p1 depends on the value of lsc1. It is 0 when p1 has no "pending" counter operations.

Remark As in [8], using the same technique, it is possible to design a sequentially consistent counter in which the operation read() is fast, while the operations increase() and decrease() are not.

6 SCD-BROADCAST IN ACTION (ITS POWER): LATTICE AGREEMENT TASK

Definition. Let S be a partially ordered set, and ≤ its partial order relation. Given S′ ⊆ S, an upper bound of S′ is an element x of S such that ∀ y ∈ S′ : y ≤ x. The least upper bound of S′ is an upper bound z of S′ such that, for all upper bounds y of S′, z ≤ y. S is called a semilattice if all its finite subsets have a least upper bound. Let lub(S′) denotes the least upper bound of S′.

Let us assume that each process p1 has an input value in1 that is an element of a semilattice S. The lattice agreement task was introduced in [6] and generalized in [16]. It provides each process with an operation denoted propose(), such that a process p1 invokes propose(in1) (we say that p1 proposes in1); this operation returns an element z ∈ S (we say that it decides z). The task is defined by the following properties, where it is assumed that each non-faulty process invokes propose().

• Validity. If process p1 decides out1, we have in1 ≤ out1 ≤ lub({in1, . . . , inn}).
• Containment. If p1 decides out1 and p1 decides outj, we have out1 ≤ outj or outj ≤ out1.
• Termination. If a non-faulty proposes a value, it decides a value.

Algorithm. Algorithm 5 implements the lattice agreement task. It is a very simple algorithm, which scd-broadcasts one message and waits for its local reception. The text of the algorithm is self-explanatory.

Theorem 4. Algorithm 5 solves lattice agreement.

Remark 1. SCD-broadcast can be built on top of read/write registers (see below Algorithm 5). It follows that the combination of Algorithms 5 and Algorithm 6 provides us with a pure read/write algorithm solving the lattice agreement task. As far as we know, this is the first algorithm solving lattice agreement, based only on read/write registers.

Remark 2. Similarly to the algorithms implementing snapshot objects and counters satisfying sequential consistency (instead of linearizability), Algorithm 5 uses no message syncc.

Let us also notice the following. Objects are specified by "witness" correct executions, which are defined by sequential specifications. According to the time notion associated with these sequences we have two consistency conditions: linearizability (the same "physical" time for all the objects) or sequential consistency (a logical time is associated with each object, independently from the other objects). Differently, as distributed tasks are defined by relations from input vectors to output vectors (i.e., without referring to specific execution patterns or a time notion), the notion of a consistency condition (such as linearizability or sequential consistency) is meaningless for tasks.

7 THE COMPUTABILITY POWER OF SCD-BROADCAST (ITS LIMITS)

This section presents an algorithm building SCD-broadcast on top of SWMR snapshot objects. (Such snapshot objects can be easily obtained from MWMR snapshot objects.) Hence, it follows from (a) this algorithm, (b) Algorithm 1, and (c) the impossibility proof to build an atomic register on top of asynchronous message-passing systems where t ≥ n/2 process may crash [5], that SCD-broadcast cannot be implemented in \( CAMP_{n,t} \) \( t \geq n/2 \), and snapshot objects and SCD-broadcast are computationally equivalent.

7.1 From snapshot to SCD-broadcast

Shared objects. The shared memory is composed of two SWMR snapshot objects. Let \( \epsilon \) denote the empty sequence.

• SENT[1..n]: snapshot object (initialized to \([0, \ldots , 0]\)), such that SENT[i] contains the messages scd-broadcast by p1.
• SETS_SEQ[1..n]: snapshot object (init. to \([\epsilon , \ldots , \epsilon]\)), such that SETS_SEQ[i] contains the sequence of the sets of messages scd-delivered by p1.

The notation \( \circ \) is used for the concatenation of a message set at the end of a sequence of message sets.

Local objects. Each process p1 manages the following local objects.

• sent1: local copy of the snapshot object SENT.
• sets_seq1: local copy of the object SETS_SEQ.
Algorithm 6: An implementation of SCD-broadcast on top of snapshot objects (code for \( p_i \))

- \( to\_deliver_i \): auxiliary variable whose aim is to contain the next message set that \( p_i \) has to scd-deliver.

The function \( \text{members}(set\_seq) \) returns the set of all the messages contained in \( set\_seq \).

**Description of Algorithm 6.** When a process \( p_i \) invokes \( \text{scd}\_\text{broadcast}(m) \), it adds \( m \) to \( \text{SENT}_i[i] \) and \( \text{SENT}[i] \) to inform all the processes on the scd-broadcast of \( m \). It then invokes the internal procedure \( \text{progress()} \) from which it exits once it has a set containing \( m \) (line 1).

A background task \( T \) ensures that all messages will be scd-delivered (line 2). This task invokes repeatedly the internal procedure \( \text{progress()} \). As, locally, both the application process and the underlying task \( T \) can invoke \( \text{progress()} \), which accesses the local variables of \( p_i \), those variables are protected by a local fair mutual exclusion algorithm providing the operations enter_mutex() and exit_mutex() (lines 3 and 11).

The procedure \( \text{catchup()} \) (lines 12-17) accordingly.

Process \( p_i \) first obtains a snapshot of \( \text{SETS\_SEQ}_i \) and saves it in \( set\_seq_i \) (line 12). This allows \( p_i \) to know which message sets have been scd-delivered by all the processes; \( p_i \) then enters a "while" loop to scd-deliver as many message sets as possible according to what was scd-delivered by the other processes. For each process \( p_j \) that has scd-delivered a message set \( set \) containing messages not yet scd-delivered by \( p_i \) (predicate of line 13), \( p_i \) builds a set \( to\_deliver_j \) containing the messages in \( set \) that it has not yet scd-delivered (line 14), and locally sc-delivers it (line 16). This local sc-delivery needs to update accordingly both \( sets\_seq_i[i] \) (local update) and \( \text{SETS\_SEQ}[i] \) (global update).

When it returns from \( \text{catchup()} \), \( p_i \) strives to scd-deliver messages not yet scd-delivered by the other processes. To this end, it first obtains a snapshot of \( \text{SENT}_i \) which it stores in \( \text{SENT}_i \) (line 5).

If there are messages that can be scd-delivered (computation of \( to\_deliver_i \) at line 6, and predicate at line 7), \( p_i \) scd-delivers them and updates \( sets\_seq_i[i] \) and \( \text{SETS\_SEQ}[i] \) (lines 7-9) accordingly.

**Theorem 5.** Algorithm 6 implements SCD-Broadcast in the classical wait-free read/write model CARW\(_{n,1}[t < n]\).

8 CONCLUSION

What was the paper on? This paper has introduced a new communication abstraction, suited to asynchronous message-passing systems where computing entities (processes) may crash. Denoted SCD-broadcast, it allows processes to broadcast messages and deliver sets of messages (instead of delivering each message one after the other). More precisely, if a process \( p_i \) delivers a set of messages containing a message \( m \), and later delivers a set of messages containing a message \( m' \), no process \( p_i \) can deliver a set of messages containing \( m' \) before a set of messages containing \( m \). Moreover, there is no local constraint imposed on the processing order of the messages belonging to a same message set. SCD-broadcast has the following noteworthy features:

- It can be implemented in asynchronous message passing systems where any minority of processes may crash. Its costs are upper bounded by twice the network latency (from a time point of view) and \( O(n^2) \) (from a message point of view).

- Its computability power is the same as the one of atomic read/write register (anything that can be implemented in asynchronous read/write systems can be implemented with SCD-broadcast).

- When interested in the implementation of a concurrent object \( O \), a simple weakening of the SCD-broadcast-based atomic implementation of \( O \) provides us with an SCD-broadcast-based implementation satisfying sequential consistency (moreover, the sequentially consistent implementation is more efficient than the atomic one).
On programming languages for distributed computing. Different from sequential computing for which there are plenty of high level languages (each with its idiosyncrasies), there is no specific language for distributed computing. Instead, addressing distributed settings is done by the enrichment of sequential computing languages with high level communication abstractions. When considering asynchronous systems with process crash failures, total order broadcast is one of them. SCD-broadcast is a candidate to be one of them, when one has to implement read/write solvable objects and distributed tasks.

ACKNOWLEDGMENTS
This work was partially supported by the Franco-German DFG-ANR Project 14-CE35-0010-02 DISCMAT (devoted to connections mathematics/distributed computing) and the French ANR project 16-CE40-0023-03 DESCARTEs (devoted to layered and modular structures in distributed computing).

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