REAL-TIME SYNCHRONIZATION OF INTERPROCESS COMMUNICATIONS (U) HARVARD UNIV CAMBRIDGE MA AIKEN COMPUTATION LAB J H REIF ET AL. JUN 82 TR-25-82 UNCLASSIFIED NOOO14-80-C-0674
REAL-TIME SYNCHRONIZATION
OF
INTERPROCESS COMMUNICATIONS

by

John H. Reif
and
Paul G. Spirakis

TR-25-82
Real-Time Synchronization of Interprocess Communications

John Reif
Paul Spirakis

Harvard University
Cambridge, MA 02138

Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

June 1982

unlimited

unlimited

distributed communication, handshake, synchronization, real time response.

see reverse side.
SUMMARY

This paper considers a fixed (possibly infinite) set of distributed asynchronous processes which at various times are willing to communicate with each other.

Each process has various ports, each of which is used for communication with a distinct neighbour process. Each process can have at most one port open at any time and its other ports must be closed. Two processes handshake over a time interval $\Delta$ if their respective ports are open for mutual communication during this interval. Note that the handshake relation is a matching. Successful communication requires a handshake of at least 1 step of each process; during the one step overlap, a message can be transmitted between processes. The problem is to synchronize processes (via a distributed scheduler) so that they can successfully handshake at their will, given that the means of synchronization is some low level construct which does not guarantee the handshake property if used in an unsophisticated way.

We describe probabilistic distributed algorithms for synchronizing processes so that they can handshake at will. The means of synchronization are boolean "flag" variables, each of which can be written by only one process and read by at most one other process. The use of flag variables seems as to require the fewest assumptions possible without considering specific systems. A process is considered to be tame over a time interval $\Delta$
Real-Time Synchronization of Interprocess Communications

20. (Continued)

if its speed varies within certain arbitrarily fixed nonzero bounds.

We show our synchronization algorithms have real time response:

If a pair of processes are mutually willing to communicate within a
time interval $\Delta$ of length at least a given constant and the pair are tame
on $\Delta$, then they establish communication within $\Delta$ with high likelihood (for
the worst case behavior of the system and the expected time for establishment
of communication is also constant. We feel the term real time is merited,
for the actual time needed for establishment of communication is upper
bounded by a constant with overwhelming probability; furthermore, violations
of this property occur with vanishingly low likelihood.

We have very few assumptions: (1) Tameness is required of a process
only during the interval it is willing to communicate (if the tameness
property is violated during that interval, then there may be lower probability
of successful communication); at other times any process may dynamically vary
its speed arbitrarily and may even die. (2) The processes may be willing to
communicate with a time varying set of processes which are only bounded in
number. There are no probability assumptions about system behavior.

Our communication model and synchronization algorithms are quite robust.
They are applied, in [Reif, Spirakis, 82b] and in our Appendix, to solve a
large class of real time resource allocation problems, as well as real time
implementation of the synchronization primitives of Hoare's multiprocessing
language CSP.
REAL-TIME SYNCHRONIZATION OF INTERPROCESS COMMUNICATIONS*

by

John H. Reif and Paul G. Spirakis
Harvard University
Aiken Computation Laboratory
Cambridge, MA 02138

June 1982

*This work was supported in part by the National Science Foundation Grant NSF-MCS79-21024 and the Office of Naval Research Contract N00014-80-C-0674.
SUMMARY

This paper considers a fixed (possibly infinite) set of distributed asynchronous processes which at various times are willing to communicate with each other.

Each process has various ports, each of which is used for communication with a distinct neighbour process. Each process can have at most one port open at any time and its other ports must be closed. Two processes handshake over a time interval $\Delta$ if their respective ports are open for mutual communication during this interval. Note that the handshake relation is a matching. Successful communication requires a handshake of at least 1 step of each process; during the one step overlap, a message can be transmitted between processes. The problem is to synchronize processes (via a distributed scheduler) so that they can successfully handshake at their will, given that the means of synchronization is some low level construct which does not guarantee the handshake property if used in an unsophisticated way.

We describe probabilistic distributed algorithms for synchronizing processes so that they can handshake at will. The means of synchronization are boolean "flag" variables, each of which can be written by only one process and read by at most one other process. The use of flag variables seems as to require the fewest assumptions possible without considering specific systems.† A process is considered to be tame over a time interval $\Delta$

† Note that we do not use any standard high level synchronization construct such as shared variables with a mutual exclusion mechanism. If we did, then we would have to assume an implementation of such a mechanism and there are no real time implementations of such mechanisms (in fact, there is no bounded time implementation of such mechanisms when processes run on different processors). We hope in the future that our techniques rather than other "standard" but inefficient synchronization mechanisms will be utilized for real time process synchronization.
if its speed varies within certain arbitrarily fixed nonzero bounds.

We show our synchronization algorithms have real time response:

If a pair of processes are mutually willing to communicate within a time interval $\Delta$ of length at least a given constant and the pair are tame on $\Delta$, then they establish communication within $\Delta$ with high likelihood (for the worst case behavior of the system and the expected time for establishment of communication is also constant. We feel the term real time is merited, for the actual time needed for establishment of communication is upper bounded by a constant with overwhelming probability; furthermore, violations of this property occur with vanishingly low likelihood.

We have very few assumptions: (1) Tameness is required of a process only during the interval it is willing to communicate (if the tameness property is violated during that interval, then there may be lower probability of successful communication); at other times any process may dynamically vary its speed arbitrarily and may even die. (2) The processes may be willing to communicate with a time varying set of processes which are only bounded in number. There are no probability assumptions about system behavior.

Our communication model and synchronization algorithms are quite robust. They are applied, in [Reif, Spirakis, 82B] and in our Appendix, to solve a large class of real time resource allocation problems, as well as real time implementation of the synchronization primitives of Hoare's multiprocessing language CSP.
1. INTRODUCTION

Recently, [Rabin, 80] [Lehman and Rabin, 81], and [Francez and Rodeh, 80] have proposed probabilistic algorithms for a number of synchronization problems. This probabilistic approach (where we make no probabilistic assumptions about the system behavior, but allow our algorithms to make probabilistic choices) leads to considerably simpler algorithms (perhaps because of the locality of their decisions) and shorter proofs (perhaps because the proofs of the corresponding deterministic algorithms had to consider complex situations which would have very low probability, if probabilistic choices were taken, whereas, in proofs of probabilistic algorithms, we need only consider those simple situations which occur with high probability). The probabilistic approach may also lead to improvement in the efficiency of synchronization algorithms. An improvement in space efficiency is seen in [Rabin, 80]. We demonstrate here that a considerable improvement in time efficiency can be made by probabilistic synchronization.

This paper takes the probabilistic approach to synchronization of communication in a network of distributed, asynchronous processes. We are interested in direct interprocess communication, rather than packet switching as considered in [Valiant, 80]. Furthermore, we consider handshake communication (as in Hoare's CSP), rather than buffered communication (which is very easy to implement by message queues).

Previously [Schwarz, 80] proposed a deterministic synchronization algorithm for implementing CSP [Hoare, 78] on a fixed acyclic distributed network. Also [Lynch, 80] gave a related algorithm for resource synchronization problems. Both algorithms are considerably less time efficient than our proposed algorithm (for specific comparison of time performance, see Section 2.E). [Francez and Rodeh, 80] also propose a probabilistic solution
to synchronization of communication, but make no consideration of the time efficiency of their solution.

Our paper is organized as follows: We present in Section 2 a model for distributed communication systems; the model ignores the details of message transmission but gives a precise combinatorial specification (by time varying graphs) of the communication synchronization problem. This model also allows a precise definition of the relevant complexity measures of synchronization algorithms, such as response time. Section 3 presents our synchronization algorithms, and in Section 4 we prove various properties of the synchronization algorithms which must hold with certainty, regardless of probabilistic choice. Sections 5 and 6 give a probabilistic analysis of the performance of our algorithms. We have taken considerable effort in the design of our synchronization algorithms to improve their expected time performance. Nevertheless, our algorithms are very simple in conception and practice. The Appendix provides a real time implementation of CSP. [Reif, Spirakis, 82B] presents a further application: a real time resource granting system. We feel these applications demonstrate the broad applicability of our synchronization algorithms.
2.0 OUR MODEL FOR A DISTRIBUTED COMMUNICATION SYSTEM (DCS) AND ITS COMPLEXITY MEASURES

Let \( \Pi = \{1, 2, \ldots\} \) be a fixed, (possibly infinite) collection of processes. We assume a (global) time \( t \), on the nonnegative real line \([0, \infty]\), whereby events of the system are totally ordered. The processes of \( \Pi \) are asynchronous; their speeds may dynamically vary arbitrarily over time and may even be 0. (Thus, we allow processes to die.) The processes have no access to any global clock giving the time.

We assume that the effect of a read or write is instantaneous and that these events occur at distinct time instants, so there are never any read/write conflicts. In general, a step of a process is a finite time interval \( \Delta \) in which a single instruction is instantaneously executed at the last moment of \( \Delta \).

We also assume a global oracle \( \mathcal{O} \) which directs the willingness of processes to communicate with each other. (Note that, in applications of our distributed communication system occurring in practice, no such oracle exists, but instead each process is running some program which requires from time to time communication with other processes. An implementation of the DCS synchronizes this communication. The oracle \( \mathcal{O} \) is utilized as an artificial device for specifying worst case situations of our system where communications are required by \( \mathcal{O} \) to be made at times most difficult for our implementation.)

Intuitively, each process \( i \) wishes at various times to communicate with processes in \( \Pi - \{i\} \). All communication required by the oracle is implemented by \( i \) rather than a global centralized synchronization mechanism.
Thus system-wide communication is implemented by a distributed scheduler, the processes of \( \Pi \).

The formal model DCS (for Distributed Communication System) described below, has been designed with as few assumptions as possible and as general as possible. We are not concerned with the values of the messages communicated between the processes, but instead, with simply the establishment of communication. This allows us to avoid any message system dependent assumptions which may vary for any given application.

We now introduce some graphs to describe precisely the DCS model. The graphs allow us to state the synchronization problems precisely as combinatorial problems on time varying graphs. We give an intuitive description of the importance of these graphs as they are defined.

Let the connections graph \( H = (\Pi,E) \) be a (possibly infinite) undirected graph with vertex set \( \Pi \) and undirected edge set \( E \subseteq (\Pi \times \Pi) - \{(i,i) | i \in \Pi\} \). Then \( \{i,j\} \in E \) denotes that \( i \in \Pi \) is physically able to communicate with \( j \in \Pi - \{i\} \) (See Figure 1A). \( H \) is fixed for all time and can be considered to be essentially the hardware connections between processes of \( \Pi \). We assume \( H \) has finite valence (i.e. only a finite number of processes are connected to any given process \( i \in \Pi \)).

For each time \( t \geq 0 \), the willingness digraph \( G_t = (\Pi,\vec{t}) \) is a possibly infinite digraph with vertices \( \Pi \) and directed edges given by relation \( \vec{t} \subseteq \Pi \times \Pi \) (See Figure 1B). Then \( \vec{t} \) denotes that \( i \in \Pi \) is willing to communicate with \( j \in \Pi - \{i\} \) at time \( t \). In that sense we say \( i \) is the source and \( j \) is the target. We require that \( \vec{t} \) implies \( \{i,j\} \in E \) so \( i \) is willing to communicate only with processes which \( i \) is able to communicate with. Also, let \( \vec{t} \) jiff both \( \vec{i} \) j and \( j \vec{i} \). We use
\( \Delta \) and \( \mathcal{L} \) to denote that the willingness to communicate holds over time intervals. For each time interval \( \Delta \) on \( (0, \infty) \), let \( i \xrightarrow{\Delta} j \) if \( i \xrightarrow{t} j \) for all \( t \in \Delta \) and let \( i \xrightarrow{\mathcal{L}} j \) if both \( i \xrightarrow{\Delta} j \) and \( j \xrightarrow{\Delta} i \). The edges of \( G_t \) departing from \( i \in \Pi \) are assumed to be stored locally at \( i \) in the form of a variable set \( E_i \) which, at time \( t \), contains the names of the targets of \( i \). \( E_i \) is specified by the oracle and read only by \( i \).

In the following we assume that there exists a given fixed integer constant \( v > 0 \) such that \( \forall i \in \Pi, \forall t \geq 0 \), the outdegree of \( i \) in \( G_t \) (i.e., the cardinality of \( \{ j \mid i \xrightarrow{\mathcal{L}} j \} \)) is bounded above by \( v \).

Assumption A1 Two-way communication between any two processes \( i,j \in \Pi \) requires only one step of \( i \) and \( j \). (Thus, \( i,j \) are assumed to communicate in short "bursts.")

2.A Implementation of a DCS

An implementation of a DCS assigns a fixed program to each of the processes of \( \Pi \). The implementation is symmetric if the programs are independent of the position of \( i \) in the connections graph \( \mathcal{H} \).

For each \( i,j \in \Pi \) such that \( \{i,j\} \in E \) we have a communication port flag \( \text{PORT}_{i,j} \) (written only by process \( i \)) which is \( 1 \) at time \( t \geq 0 \) if \( i \) has opened its port for communication with \( j \) at \( t \), and \( 0 \) otherwise (indicating the communication port from \( i \) to \( j \) is closed at \( t \)). We assume 2-way communication between \( i,j \) is possible at any time that both \( \text{PORT}_{i,j} \) and \( \text{PORT}_{j,i} \) are simultaneously \( 1 \), but we make no particular assumptions (beyond A1 and A2 below) about this communication.

Let \( i \xrightarrow{t} j \) denote that \( \text{PORT}_{i,j} = 1 \) at time \( t \). For each \( t \geq 0 \) our implementation defines a (possibly infinite) directed graph \( \mathcal{M}_t \) with
vertices \( V \) and directed edges given by the relation \( \overset{t}{\to} \subseteq \mathbb{N} \times \mathbb{N} \). Let \( i \overset{t}{\leftrightarrow} j \) if both \( i \overset{t}{\to} j \) and \( j \overset{t}{\to} i \). If \( i \overset{t}{\to} j \) then we say \( i \) has opened communication with \( j \in \mathbb{N} \setminus \{i\} \) at \( t \). If \( i \overset{t}{\leftrightarrow} j \) then we say \( i,j \) achieve mutual communication at time \( t \). Also, we extend the notation to intervals \( \Delta \) on \((0,\infty)\) as for \( G_t \).

**Assumption A2** If \( i \overset{t_1}{\to} j \) and not \( i \overset{t_2}{\to} j \), \( t_2 > t_1 \), then \( i \overset{\Delta}{\leftrightarrow} j \) for some \( \Delta \in [t_1, t_2) \), where \( \Delta \) contains at least one step of each \( i \) and \( j \); i.e. the oracle \( \mathcal{O} \) can withdraw willingness to communicate only after communication has been established and completed.

An implementation is proper if it satisfies the following restrictions:

- **R1** \( i \overset{t}{\to} j \) only if \( i \overset{t}{\leftrightarrow} j \)

- **R2** \( i \overset{t}{\leftrightarrow} j \) is a (partial) matching; if \( i \overset{t}{\leftrightarrow} j \) then not \( i \overset{t}{\leftrightarrow} j' \) for any \( j' \in \mathbb{N} \setminus \{j\} \).

Note that **R1** implies that \( i \) opens communication with \( j \) only if \( i,j \) are simultaneously willing to communicate. **R2** implies that \( i \) does not communicate with more than one process at a time.

It is standard in the study of combinatorial algorithms to specify the combinatorial problem before giving algorithms for the solution. We have precisely described the problem of determining a DCS implementation as a combinatorial problem on dynamic graphs. Later we shall propose two implementations satisfying both these restrictions. Still another implementation is described in [Reif, Spirakis, 81B].
2.B. Global State of the DCS

For each \( t \geq 0 \), let \( R_t \) be a mapping from \( \Pi \) to the nonnegative reals giving the speed of each process of \( \Pi \) at time \( t \). We assume the speed schedule \( R = \{ R_t \mid t \geq 0 \} \) is chosen by an adverse oracle \( \mathcal{A} \) (possibly our scheduler's worst "enemy") \textit{a priori} (at time \( t = 0 \)). Also, we assume for each \( t \geq 0 \), \( \mathcal{A} \) chooses for the processes of \( \Pi \) the willingness digraph \( G_t \) at time \( t \). Thus, \( G_t \) may vary dynamically in time, depending on the choices of the oracle \( \mathcal{A} \). However, for each \( t \geq 0 \), the digraph \( M_t \) is defined by the processes of \( \Pi \), which attempt a distributed synchronization of the DCS, depending on our given implementation. In addition, we allow the processes of \( \Pi \) to make independent probabilistic choices.

Let \( L_t \), the \textit{luck up to time} \( t \), to be the probabilistic choices made by the processes of \( \Pi \), up to time \( t \). Then, the \textit{global system state} at time \( t \) is given by

\[
\Sigma_t = \{ R_t, G_t, M_t, L_t, t \}
\]

and the \textit{global history} up to time \( t \) is

\[
\Gamma_t = \{ \Sigma_t, |0 \leq t' \leq t \}
\]

Thus, we have a probabilistic multiplayer game of incomplete information, where the omnipotent oracle \( \mathcal{A} \) plays against the team of processes of \( \Pi \) which have only incomplete information on the current state of the system. We wish measures of the success of the processes of \( \Pi \).
2.C. **Time Complexity of a DCS Implementation**

A process step consists of either an assignment of a variable, a test, a logical or arithmetic operator, or a no-op.

Let process \( i \) be tame on an interval \( \Delta \), if for any interval \( \Delta' \in [0, \infty) \), if \( \Delta' \) intersects \( \Delta \) and \( \Delta' \) is a single step of process \( i \), then \( |\Delta'| \in [r_{\min}, r_{\max}] \), where \( r_{\min}, r_{\max} \) are fixed real constants and \( 0 < r_{\min} \leq r_{\max} \). (without loss of generality we assume that \( r_{\max}/r_{\min} \) is an integer.)

We shall not assume that processes are tame at all times. Our DCS implementation will be proper regardless of whether processes are tame as long as their speeds are nonzero.

Let processes \( i,j \) have successful communication at interval \( \Delta \) if \( i \Leftarrow \Delta \rightarrow j \) and \( \Delta \) contains at least one step of both \( i \) and \( j \). We say \( \Delta \) is a response interval for processes \( i,j \) if \( \Delta \) is a maximal time interval such that

1. \( i \Leftarrow \Delta \rightarrow j \),
2. \( i,j \) are both tame on \( \Delta \), and
3. \( i,j \) have successful communication at most just at the end of \( \Delta \), if at all.

Note that if there is successful communication during an interval \( \Delta' \) within \( \Delta \), then, by (3), \( \Delta' \) is a suffix of \( \Delta \). Also, note that since is maximal, either \( i,j \) were not mutually willing to communicate immediately before \( \Delta \), or \( \Delta \) begins at time 0, or the instant immediately before \( \Delta \) is the end of a previous response interval.

Let a communication request be \( R = (t,i,j) \) such that \( t \) is the starting instance of a response interval for processes \( i,j \).
Note that there is a unique communication request associated with each response interval.

Let the response time of a DCS implementation, for any oracle \( \mathcal{A} \) and communication request \( R \), be the random variable \( \tau_{\mathcal{A}, R} \) giving the length of the response interval associated with \( R \). Let \( \bar{\tau} = \max_{i} \text{mean}(\tau_{\mathcal{A}, R}) \) for each oracle \( \mathcal{A} \) and communication request \( R \).

For each \( \varepsilon, 0 < \varepsilon < 1 \), let the \( \varepsilon \)-error response \( \tau(\varepsilon) \) (note: this is a function, not a random variable) be the least upper bound on the set of the values of the inverse functions of the cumulative distribution functions of \( \tau_{\mathcal{A}, R} \) at \( 1-\varepsilon \), for all \( \mathcal{A} \) and \( R \). Thus, if we have a finite interval \( \Delta, |\Delta| \geq \tau(\varepsilon) \) and any two processes \( i, j \) which are tame on \( \Delta \), for all oracles \( \mathcal{A} \), \( i \overset{\mathcal{A}}{\rightarrow} j \) implies \( i, j \) have successful communications sometime within \( \Delta \) with probability \( \geq 1-\varepsilon \).

Note that time response as defined above for pairs of processes also holds for communication between sets of processes. Suppose we have finite sets or processes \( \Pi_1, \Pi_2 \subseteq \Pi \) such that \( |\Pi_1|, |\Pi_2| \leq v \) and for the same interval \( \Delta \) of length \( \geq \tau(\varepsilon) \) and for all \( i \) in \( \Pi_1 \) and all \( j \) in \( \Pi_2 \), \( i \overset{\mathcal{A}}{\rightarrow} j \). Then, each process \( i \) of \( \Pi_1 \) is guaranteed at least \( (1-\varepsilon, |\Pi_2|) \) probability of successful communication with all the processes of \( \Pi_2 \), within \( \Delta \). This implies a very robust type of fairness.

The DCS implementation is real time if for all \( \varepsilon, 0 < \varepsilon < 1 \), \( \tau(\varepsilon) \) is a constant dependent only on \( v \) (assumed to be a constant upper bound on the outdegree of vertices of \( G_t \)). Note then that \( \bar{\tau} \) is also bounded above by a fixed constant dependent only on \( v \).
2.D. Preferential DCS Implementations

We also consider the cases where any given process \( i \in \Pi \) may assign a priority to the processes \( j \in \Pi - \{i\} \) which \( i \) wishes to communicate with. In the simplest case, which we only consider here, \( i \) distinguishes the first target of communication, \( E_i(1) \), which \( i \) prefers to communicate with. (Process \( i \) may communicate with the other processes of \( E_i \), but \( i \) prefers to communicate with \( E_i(1) \).)

For each \( t > 0 \), \( \tau' \) is the relation on \( \Pi \times \Pi \) such that \( \forall t \), \( j \in \Pi \)

\[ i \tau' j \iff E_i(1) = j \text{ at time } t. \]

Also let \( i \tau'_o j \iff i \tau'_0 j \forall t \in \mathbb{Z} \).

We say \( \Delta \) is a preferential response interval for \( i, j \) if \( \Delta \) is a maximal interval such that

1. \( i \tau'_o j \) and \( j \tau'_o i \)
2. \( i, j \) are both tame on \( \Delta \), and
3. \( i, j \) have successful communication at most just at the end of \( \Delta \).

(Note that only the first process has to distinguish the other as the first target.)

Let a preferential communication request \( R = (t, i, j) \) be such that \( t \) is the starting instant of a preferential response interval for \( i, j \).

Note that there is a unique \( R \) associated with each response interval.

We now define the time complexity of preferential DCS implementations in a similar way: Let the preferential response time of a DCS implementation for any oracle \( \mathcal{A} \) and preferential communication request \( R \) be the random variable \( T'_o R \) which gives the length of the preferential response interval associated with \( R \).

Let \( \bar{T}' = \max\{\text{mean}(T'_o R) \} \) for all oracles \( \mathcal{A} \) and communication requests \( R \).
For each $\varepsilon$, $0 < \varepsilon \leq 1$, let the $\varepsilon$-error preferential response $\tau'(\varepsilon)$ be the least upper bound on the set of the values of the inverse functions of the cumulative distribution functions of $T_{i,N}$, each evaluated at $1-\varepsilon$, for all $N$ and $R$.

Thus, if we have a finite interval $\Delta$, $|\Delta| \geq \tau'(\varepsilon)$ and any two processes $i,j$ which are tame on $\Delta$, for every oracle $\mathcal{N}$, $(i \nless j$ and $j \nless i)$ implies $i,j$ have successful communication sometimes within $\Delta$, with probability $\geq 1-\varepsilon$.

The DCS implementation has real time preferential response if for all $\varepsilon$, $0 < \varepsilon \leq 1$, $\tau'(\varepsilon)$ is a constant dependent only on $\nu$ (and not on any parameter of $H$). Note then that $\tau'$ is also bounded above by a constant dependent only on $\nu$.

It is useful to observe that, given $\tau'(\varepsilon)$, any given process $i \in \mathbb{N}$ may determine (with any given probability) whether any process $j \in \mathbb{N} - \{i\}$ is willing to communicate with $i$ over a given time interval in which both $i,j$ are tame, given $\{i,j\} \in H$. The same holds if $\tau(\varepsilon)$ is given instead of $\tau'(\varepsilon)$.

PROPOSITION 2.1. Let $\mathcal{N}$ be any oracle and $\Delta$ be any time interval of finite length $\geq \tau'(\varepsilon)$ ($\tau'(\varepsilon)$ in the case of preferential DCS.) Suppose $i,j$ are tame on $\Delta$ and $\{i,j\} \in H$. If there is no $t \in \Delta$ such that $i \nless \tau_j t$, then $j$ is not willing to communicate with $i$ sometime within $\Delta$, with probability $\geq 1-\varepsilon$.

This proposition may be used for timing out requests (or preferential requests) to communicate with a specific process.

(Note: Suppose we are given a process $j$, a set of processes $\Pi_1 \subseteq \Pi$ and an interval $\Delta \geq \tau'(\varepsilon)$ such that for all $i \in \Pi_1$, $i \nless j$ and
Assume also, all processes in $\Pi_j \cup \{j\}$ are tame on $\Lambda$. Then, for each $i \in \Pi_j$ and for all oracles $\mathcal{A}$, $i,j$ have successful communication sometime with $\Lambda$, with probability $\geq 1 - \varepsilon$. Furthermore, if $|\Pi_j| \leq v$, then, for all oracles $\mathcal{A}$, $j$ will have successful communication with all $i \in \Pi_j$ within $\Lambda$, with probability $\geq (1 - \varepsilon)^{|\Pi_j|}$.

2.E. Results and Previous Work

The primary results of this paper are:

There is a proper real time implementation of DCS such that

1. the worst case mean response $\bar{T}$ is $O(v^2)$.
2. the $\varepsilon$-error response $T(\varepsilon)$ is $O(v^2 \log(\frac{1}{\varepsilon}))$.

Also, there is a real time preferential implementation of DCS such that

1. worst case mean preferential response $\bar{T}'$ is $O(v)$;
2. the $\varepsilon$-error preferential response $T'(\varepsilon)$ is $O(v \log(\frac{1}{\varepsilon}))$.

Our implementations are proper, symmetric, and are completely independent of the connection graph $H$ ($H$ may be any finite or infinite graph with finite valence). We allow processes to make probabilistic choices and show that our algorithms have real time response.

The best previous result is due to [Schwarz, 80] and is restricted to the case $H$ is finite and its edges can be directed to form a digraph $H'$ which is acyclic. Let $\chi(H)$ be the minimum vertex coloring of any such $H'$. Essentially, the technique of [Schwarz, 80] is to color $H'$ and order the precedence of message transmissions by the coloring. Delays in message transmissions can be as long as $\chi(H)$ since chains of processes (of length $\chi(H)$) can be formed in which each process waits for the next to reply. So the deterministic DCS implementation of [Schwarz, 80] has preferential response
time $T'$ lower bounded by $v^*\chi(H)$. Note that his implementation is not real time, since in general $\chi(H)$ is of size $|\Pi|$. In contrast, in our implementation, the time-varying willingness digraph is assumed to have bounded outdegree, but we see no way of Schwarz's algorithm to take advantage of this. Also, his DCS implementation is not symmetric, since processes are required to know their color in $H'$.

Also, [Lynch, 80] gives a solution to a distributed resource allocation problem which in [Reif, Spirakis, 82B] is adopted to yield a DCS implementation with response time $v^*\chi(H)$. In [Reif, Spirakis, 82B] we show that a class of generalized resource allocation problems related to those of [Lynch, 80] may be solved in real time by our DCS implementation (with vanishingly small probability of violation of the real time property).

[Francez, Rodeh, 80] proposed a probabilistic synchronization algorithm which can be considered to be DCS implementation. An important difference between our implementation and theirs is that in the responding phase, in our algorithms, each process responds to all processes to which it is willing to communicate, while in [Francez, Rodeh, 80] only one process is considered at a time. Although [Francez, Rodeh, 80] make no explicit timing assumptions, they do assume that setting and resetting of shared variables takes only a negligible time compared to the waiting time of processes, which is a much stronger assumption than ours. The careful consideration of timing in our paper is crucial to our achievement of real time response (see also the analysis) and such timing considerations were essentially not considered in any previous papers on synchronization.
3. OUR IMPLEMENTATION OF A DCS

To implement a DCS, we must give an algorithm for each process in \( \mathcal{N} \). We present here two such implementations. Both satisfy restrictions R1, R2 required by proper implementations, and both are symmetric: Each process has the same algorithm regardless of its position in the graph \( H \).

Processes have Algorithm 1 in our "non-preferential" implementation, and Algorithm 2 in our "preferential" implementation. We show in Section 4 that both implementations have real time response.

Each program variable \( X \) of the system may be written by exactly one process \( i \in \mathcal{N} \) and either \( X \) is read by only one other process \( j \in \mathcal{N} - \{i\} \) (in this case \( X \) is a flag from \( i \) to \( j \)) or \( X \) is local to \( i \) (\( X \) is read only by \( i \)).

Our following description of the DCS implementations will be given top-down with a high level specification of the algorithms given first and then a specification of the procedures ASK, RESPOND which they call. (The procedures ASK, RESPOND utilize numerous flag variables which are irrelevant to the overall understanding of our algorithms.) Also, before giving the formal specifications of any algorithm or procedure, we provide an informal description of its actions. The actual formal algorithms have been written carefully to satisfy certain timing restrictions required by our analysis to achieve real time response.

In both algorithms, each process repeatedly throws a fair coin and then executes a phase. Each phase is either asking or responding and is chosen by the coin throw with probability \( 1/2 \). This is used to ensure each process is in either phase half of the time or the average.
Informal Description of the Non-preferential Algorithm 1

In a responding phase, process $i$ repeats a loop $m$ times, where $m = (v+3) \cdot \frac{r_{\text{max}}}{r_{\text{min}}} + 1$. On each iteration of the loop, process $i$ chooses at random a process $j$ from the processes $i$ is willing to communicate with, and executes procedure $\text{RESPOND}_i(j)$. This procedure takes constant $c_R$ number of steps. During these steps process $i$ reads a flag to determine if $j$ has recently been willing to talk to $i$ and then sets a flag so as to later verify that $j$ pays attention to $i$. These verifications are done by handshakes. (A handshake is the use of boolean flags to verify exchange of a single bit of information). If so, processes $i$ and $j$ synchronize their steps and then both open communication to each other. In either case, $i$ repeats the loop until the corresponding phase finishes.

In an asking phase, process $i$ chooses only once at random a process $j$ with which $i$ is willing to communicate, and then $i$ executes procedure $\text{ASK}_i(j)$. This procedure takes $c_A = c_R \cdot m$ steps (so that both phases take exactly the same number of steps. As a consequence, process $i$ is in each phase half of the time on the average. This is important to the analysis). During procedure $\text{ASK}_i(j)$, process $i$ raises a flag to show to $j$ that it is currently willing to communicate with $j$, and then pays attention to $j$ for a limited number of steps to test if $j$ responds to the attempt and wants to proceed in communication. If so, then processes $i$ and $j$ synchronize their steps and then both open communication to each other. If not, then $i$ finishes its current phase by setting its flags to 0.
Informal Description for the Preferential Algorithm 2

Each process $i$ executes forever the following loop:

It chooses with probability 1/2 to execute a respond phase or a modified ask phase. The respond phase is identical to that of Algorithm 1. However, in the modified ask phase, process $i$ chooses the distinguished first process $E_i(1)$ as the process to which it will apply the procedure $ASK_i$.

Formal Definitions of Algorithms 1 and 2

We now give Algorithms 1 and 2 in full detail.

**Algorithm 1** (non-preferential implementation)

Program for process $i \in \Pi$

```
INITIALIZE_i();
WHILE TRUE DO
  BEGIN
    L2: CHOOSE a random $b \in \{0,1\}$
    IF $b = 0$ THEN
      BEGIN
        COMMENT: respond phase
        L3: FOR $x = 1$ to $m$ DO
          BEGIN
            CHOOSE at random $j \in E_i$
            RESPOND_i(j);
          END
      END
    ELSE
      BEGIN
        COMMENT: ask phase
        L4: CHOOSE at random $j \in E_i$
          ASK_i(j)
      END
  END
OD
```
Algorithm 2 (the preferential implementation)

Program for process $i \in \Pi$

$\text{INITIALIZE}_i()$

$\text{WHILE TRUE DO}$

BEGIN

L1: CHOOSE a random $b \in \{0,1\}$

IF $b = 0$ THEN

BEGIN

COMMENT: respond phase

L3: FOR $x = 1$ to $m$ DO

BEGIN

CHOOSE a random $j \in E_i$

RESPOND$_i(j)$

END

END

ELSE

BEGIN

COMMENT: ask phase

L4: ASK$_i(E_i(1))$

END

END

OD

3.A. Intuitive Description of the Procedures ASK, RESPOND

The procedures ASK$_i$, RESPOND$_i$ are utilized by both algorithms.

For each $i, j \in \Pi$ such that $(i,j) \in \mathcal{H}$ there are three flags (boolean variables) $Q_{ij}, A_{ij}, B_{ij}$ which are written only by $i$ and read only by $j$.

(1) Flag $Q_{ij}$: Just before each phase, $Q_{ij} = 0$. Then $i$ asks $j$ by setting $Q_{ij}$ to 1 in the ask phase. $Q_{ij}$ is reset to 0 before the end of the ask phase.

(2) Flag $A_{ij}$: Just before each phase, $A_{ij} = 0$. If $i$ is in the responding phase and detects $Q_{ji} = 1$ (indicating $j$ "asks" $i$) then $i$ answers $j$ by setting $A_{ij} = 1$. Before the end of the answer phase, $i$ resets $A_{ij}$ to 0.
(3) Flag $B_{ij}$: This variable is set to 1 by $i$ only during the "watching window" which is the interval when $i$ is in the asking phase and is watching for an answer ($A_{ij} = 1$) from $j$. At all other times, $B_{ij}$ is set to 0 to indicate $i$ is blind to answers by $j$.

Another flag $\text{PORT}_{ij}$ is utilized by the low level procedure $\text{OPEN-COM}$ to specify the state of the communication port from $i$ to $j$. As defined in Section 2, $i \sim \text{PORT}_{ij} \to j$ iff $\text{PORT}_{ij} = 1$ at time $t$. ($\text{OPEN-COM}$ is called by $\text{ASK}_i$ and $\text{RESPOND}_i$ as the final act in a successful communication attempt.)

If process $i$ executes $\text{ASK}_i$, then it first sets a flag variable $Q_{i,j}$ to 1 (to indicate to $j$ that it asks) and sets another flag $B_{i,j}$ to 1 to indicate to $j$ that it pays attention to it, i.e., $i$ is not blind to answers by $j$). It keeps these flags raised for at most a constant number $c_B$ steps and during these steps it continuously examines the flag $A_{j,i}$ (the answer flag of $j$). If the interval finishes with no answer from target, then $i$ first $B_{i,j}$ to 0 (to show that it stops paying attention to $j$) and then it sets $Q_{i,j}$ to 0 to drop the question. This order of actions guarantees that process $j$ will interpret correctly what it sees from the flags of $i$.

If $i$ gets an answer from $j$ (that is, if $A_{j,i}$ is set to 1) during the (previously discussed) $c_B$ steps, then $i$ first sets $Q_{i,j}$ to 0 (but keeps $B_{i,j}$ to its current value to indicate that it continues to pay attention to $j$). Process $i$ waits until $j$ also zeros its flag $A_{j,i}$ and then process $i$ calls $\text{OPEN-COM}_i(j)$ immediately. As the analysis shows, the events leading to this call guarantee that communication is achieved between $i$ and $j$ during the execution of $\text{OPEN-COM}$, assuming $i$ and $j$ are tame (we do not use a handshake protocol within $\text{OPEN-COM}$ since certain
technical constraints (see Lemma 4.6) of our analysis would be violated
(namely, if \(i\) is tame but \(j\) is not, \(i\) would unnecessarily delay in
OPEN-COM and this would cause problems to communication between \(i\) and
other tame processes). At the end of OPEN-COM, \(i\) sets \(B_{1,j}\) to 0 (showing
that it stops paying attention to \(j\)) and exits procedure \(\text{ASK}_i\).

If process \(i\) executes procedure \(\text{RESPOND}_i\) (asker), then it first
examines if \(Q_{\text{asker},i} = 1\) (i.e., if asker is interested in communicating
with \(i\)). If so, then \(i\) sets \(A_{1,\text{asker}}\) to 1 and waits until process asker
zeros its question flag (this is the "handshake" technique). When this
happens, then \(i\) tests \(B_{\text{asker},i}\) to see if process asker still pays attention
to \(i\). If not, then \(i\) zeros its answer flag \(A_{1,\text{asker}}\) and exits. Else,
\(i\) knows that asker waits for step synchronization and communication. So,
\(i\) zeros its flag \(A_{1,\text{asker}}\) and calls OPEN-COM\(_i\) (asker). The analysis
shows that the events leading to this call guarantee that communication will
be achieved.

We now introduce some terminology and then develop the algorithms in
full detail.

A process \(i\) is in the asking mode when it executes procedure \(\text{ASK}\),
and it is in the responding mode when it executes the procedure \(\text{RESPOND}\). If
\(i\) is executing \(\text{ASK}(j)\) and \(B_{1,j} = 1\) then \(i\) is in a watching window for
process \(j\) else \(i\) is blind with respect to \(j\). We say \(i\) is answered by
\(j\) if \(i\) is in its watching window for \(j\) and \(i\) exits loop A3 of procedure
\(\text{ASK}_i\) with \(a = 1\). A phase of the algorithms consists of the steps between
random choices of the variable \(b \in \{0,1\}\). If \(b = 0\) the process is in a
responding phase and else it is in an asking phase.

We have not elaborately commented on our procedures because of the
extensive informal description preceding them.
The variables of process $i$ are initialized as follows:

\begin{verbatim}
INITIALIZE($i$);
BEGIN
    for all $j \in I$ such that $\{i,j\} \in H$ do
        BEGIN
            $Q_{ij} \leftarrow 0$
            $A_{ij} \leftarrow 0$
            $B_{ij} \leftarrow 0$
            PORT$_{ij} \leftarrow 0$
        END
END
\end{verbatim}

In the following two procedures, we assume a register CURSTEP which gives the current number of the steps executed by process $i$ since it was last zeroed. (CURSTEP is assumed here only as a convenience, it is clear that we could substitute instead a new variable that is incremented on every step of the original Algorithm.)

We have made extensive use of time outs to guarantee that the number of steps of the execution of procedures RESPOND, ASK are each always exactly the same. (This is crucial to our proof of real time response.)

We define the parameters appearing in the procedures:

Let $c_R = 7 + (12 + 4\frac{r_{\max}}{r_{\min}})\frac{r_{\max}}{r_{\min}}$; this will be precisely the number of steps always required by procedure RESPOND (see justification in Lemma 4.3).

Let $m = (v+3)\frac{r_{\max}}{r_{\min}} + 1$. Let $c_A = c_R \cdot m$; this will be the number of steps required by procedure ASK. Let $c_B = c_A - c_R$; this is the number of steps required for a watching window. Let $c_F = 2 + 3\frac{r_{\max}}{r_{\min}}$; this is the number of steps required in procedure OPEN-COM. Let $c_D = c_A - c_F - 2$ and $c_E = c_R - 7$.

These parameters are used to time-out the execution of various loops in our algorithms.
PROCEDURE ASK, (target)
local a
BEGIN
A1: CURSTEP + 0
A2: Q_i, target + 1
a + 0
B_i, target + 1
COMMENT: Begin watching window for target
A3: WHILE CURSTEP < c_B AND a = 0 DO a + A_target, i
IF CURSTEP > c_B AND a = 0 THEN B_i, target + 0
Q_i, target + 0
IF a = 1 THEN
BEGIN
A4: WHILE (A_target, i = 1 AND CURSTEP < c_D) DO a + A_target, i
A5: IF a = 0 AND CURSTEP < c_D THEN OPEN-COM, (target)
END
COMMENT: End watching window for target
B_i, target + 0
WHILE CURSTEP < c_A DO a nonoperative step.
END

PROCEDURE RESPOND, (asker)
local q
BEGIN CURSTEP + 0
q + Q_asker, i
B1: IF q = 1 THEN
BEGIN
A_i, asker + 1
B2: WHILE (CURSTEP < c_E AND q = 1) DO q + Q_asker, i
q + (q OR B_i, asker = 1 OR CURSTEP > c_E)
B3: A_i, asker + 0
IF q THEN B4: OPEN-COM, (asker)
B5: WHILE CURSTEP < c_R DO a nonoperative step
END
PROCEDURE OPEN-COM\textsubscript{i}(j)

BEGIN

PORT\textsubscript{i} + 1

DO \textsubscript{c_p} = 2 nonoperative steps

PORT\textsubscript{i} - 1

END

4.A. Correctness Properties of the Algorithms which Hold with Certainty

Our algorithms are probabilistic and therefore some of their properties (such as response time) only hold with a certain probability, and not with certainty. A probabilistic analysis of these properties is given in the next sections. However, in this section we prove properties of the algorithms which hold with certainty, regardless of probabilistic choice. We show restrictions R1, R2 are satisfied by our implementations, and thus they are proper. (Of course, we assume either all the processes in \Pi execute Algorithm 1, or they all execute Algorithm 2.)

LEMMA 4.1. For both algorithms,

\[ \xrightarrow{t} i \iff \xrightarrow{t} j. \]

Proof. Process \( i \) calls OPEN-COM\textsubscript{i}(j) and opens its channel to \( j \) only if either (a) \( i \) was executing an asking phase and exited the loop A3 with \( a = 1 \) or (b) \( i \) was executing a respond phase and exited the busy wait B2 with \( B_{j,i} = 1 \). In both cases, \( i \) was willing to communicate with \( j \) in the start of the execution of its phase, since \( i \) asks (or responds) only to processes it is willing to communicate with. So, \( \xrightarrow{t} i \iff \xrightarrow{t} j \) where
t' was the time of start of i's phase. By assumption (A2) then, 
\[ i \rightarrow j \]
In case (a), \( a = 1 \) means that j responded by setting \( A_{j,i} \) to 1 to i's question. So, \( j \rightarrow i \) for some \( t'' < t \) and by assumption (A2), 
\[ j \rightarrow i \]
In case (b), j was the process setting \( q_{j,i} \) to 1 at the beginning of i's phase. Hence \( j \rightarrow i \) and, by (A2), \( j \rightarrow i \).
In both cases, \( i \rightarrow j \) implies \( i \rightarrow j \).

**LEMMA 4.2.** For both algorithms, 
\[ \rightarrow \] is a partial matching.

**Proof.** Since each process opens communication to at most one process each time, (this is so since the programs in both algorithms are sequential and each neighbor is asked or responded to separately), the relation \( \rightarrow \) is one to one. Hence \( \rightarrow \) cannot be more than a matching.

**COROLLARY 4.1.** Both algorithms give a proper implementation of DCS.

4.B. **Timing Lemmas Which Hold With Certainty**

Timing is an important aspect of our algorithms. The following lemmas are essential, but somewhat tedious to prove.

**LEMMA 4.3.** Assume \( i,j \) are tame. For both algorithms, if i is answered by j, then \( i,j \) have successful communication, within 
\[ (12 + 4 \frac{r_{\text{max}}}{r_{\text{min}}}) \] steps of the slower of \( i,j \) from the time i exits loop A3.
Proof. If \(i\) exits the A3 loop with \(a = 1\), then (since no process but \(j\) can assign to \(A_{j,1}\)) at the same time \(j\) must be executing
RESPOND\(_j\)'(i) at the B2 loop. Process \(i\) will arrive at A4 within 4 of its steps and will have by then set \(Q_{ij}\) to 0. These 4 steps of \(i\) correspond to at most \(4 \frac{r_{\text{max}}}{r_{\text{min}}}\) steps of \(j\), during which \(j\) will have exited the B2 loop. Also at this time, the assumption that \(i\) exits the loop A3 with \(a = 1\) implies that \(B_{ij} = 1\). So, \(j\) will arrive at B3 and set \(A_{j,1}\) to 0 in at most 4 of its steps from the time it exited the B2 loop.

Within \(\frac{r_{\text{max}}}{r_{\text{min}}}\) steps of \(i\), process \(i\) exits the A4 loop. Then, within two of \(i\)'s steps \(i\) will call OPEN-COM\(_i\)'(j) and within one of \(j\)'s steps \(j\) will call OPEN-COM\(_j\)'(i). Note that both \(i, j\) will set their respective port flags \(\text{PORT}_{ij}, \text{PORT}_{ji}\) to 1 within one step of the slower process (or, within at most \(\frac{r_{\text{max}}}{r_{\text{min}}}\) steps of the faster). They keep their ports open for \(c_p - 2 = 3 \frac{r_{\text{max}}}{r_{\text{min}}}\) steps each. This implies that both processes will overlap for at least \(2(\frac{r_{\text{max}}}{r_{\text{min}}} \cdot r_{\text{min}} = 2 \frac{r_{\text{max}}}{r_{\text{min}}}\) time, guaranteeing at least 1 step overlap of both processes. Thus, \(i, j\) have successful communication. Note that OPEN-COM takes \(c_p\) steps.

Counting steps of \(i\) plus those of \(j\) in nonoverlapping time intervals, we have a total of \(4 + 4 + \frac{r_{\text{max}}}{r_{\text{min}}} + 2 + c_p = 12 + 4 \frac{r_{\text{max}}}{r_{\text{min}}}\) which is certainly an upper bound to the steps of the slowest of the two processes.\(\square\)

**Lemma 4.4.** For both algorithms, if \(i, j\) are tame on \(\Delta'\) and \(i \xrightarrow{\Delta'} j\) for a maximal interval \(\Delta'\), then \(\Delta'\) contains at least a step of both \(i\) and \(j\) and \(|\Delta'| = \Theta(1)\). (This ensures that \(\Delta'\) is just long enough for \(i, j\) to communicate.)
Proof. The only sequence of events leading to this is the sequence in which one of $i,j$ is in its watching window for the other and is answered by the other. By Lemma 4.3, then, $\Delta'$ contains a step of both $i,j$. Since $\Delta'$ is not greater than $c_p$ steps of either process, then $|\Delta'| \leq c_p r_{\max} = 2r_{\max} + 3r_{\max}^2/r_{\min}$.

**Lemma 4.5.** For both algorithms, if $i,j$ are tame on $\Delta$ and $i \rightarrow j$ for a maximal interval $\Delta$, then $i \rightarrow j$ for some $\Delta' \subseteq \Delta$. Furthermore, $i,j$ have successful communication during $\Delta'$. (I.e., a tame process never opens its channel to another tame process without communicating with it.)

Proof. The only sequence of events leading to $i \leftarrow j$ is the sequence in which one of $i,j$ was in its watching window for the other and is answered by the other. By Lemma 4.3, $\exists \Delta' \subseteq \Delta$ such that $i,j$ have successful communication during $\Delta'$.

In the following lemma, we need not necessarily assume that $i$ is tame.

**Lemma 4.6.** If $i \in \Pi$ executes procedure ASK, then precisely $c_A$ steps of $i$ are required for the execution of this procedure. Execution of RESPOND by $i$ requires precisely $c_R$ steps of $i$. Also, each phase of either Algorithm 1 or Algorithm 2 requires exactly $c_A + 2$ steps.

Proof. By observation of timeouts within the procedures ASK and RESPOND and by the definition of $c_A = m \cdot c_R$.

Let $c = m/v \cdot c_R$. Then $c \cdot v$ is the number of steps required for each phase.

**Corollary 4.2.** The time required for each phase is upper bounded by $cv_{\max}$. 
5. PROBABILISTIC ANALYSIS OF THE RESPONSE TIME OF THE ALGORITHMS

Intuitively, in both algorithms, the ASK or Respond phases take $O(v)$ time each. In the worst case of the non-preferential algorithm, it requires $O(v)$ expected executions of the ASK phase to choose any given willing neighbor, if the set of willing neighbors is $O(v)$. Given that a given neighbor is chosen and he is willing, communication will be achieved with probability bounded below a constant. Hence, we expect the average time of response of the non-preferential algorithm to be $O(v^2)$.

On the other hand, in the asking phase of the preferential algorithm we ask a specific neighbor and we have a constant probability to communicate with him, if he is willing. Thus, the expected total number of phases will be $O(1)$ and so the expected response time of the preferential algorithm will be $O(v)$ in the worst case.

A formal analysis follows:

By Corollary 4.2, $cv$ is the total number of steps of the asking or responding phase and fix throughout this section $I$ to be an interval, starting at time $t_0$, of length at least 4 phases (i.e., $|I| \geq 4cvr_{\max}$).

Let $\Gamma_{t_0}$ be the global system history up to $t_0$ and let $A$ be a fixed oracle. Note that $(A, \Gamma_{t_0})$ essentially specifies everything of the system's immediate future except "luck" $L_{t_0}$, for $t' > t_0$. Consider two processes $i,j$ such that $\{i,j\} \in H$ and $i \mapsto j$ and $i,j$ tame on $I$.

Let $t_j = \min\{t > t_0 | j \text{ does a phase selection at } t\}$ and $t_i = \min\{t > t_0 | i \text{ does a phase selection at } t\}$.

Let $t_m = \max(t_i, t_j)$ and let $t_{i1}, t_{i2}$ (and $t_{j1}, t_{j2}$) be the next two
phase selections of \(i\) (and \(j\) respectively) after \(t^m\) such that
\[t^m < t^1 < t^2\]
and
\[t^m < t^j < t^j_2\]

Let
\[t^M = \max(t^2, t^j_2)\]

The interval \((t_0, t^M]\) is called a session \(S\) of processes \(i, j\).
(See Figure 2). Note that a session has \(<3\) phases of one of the processes \(i, j\) and hence its length is \(<3cvr_{\text{max}}\).

Let \(c_{ij}(\mathcal{A}, \Gamma_0)\) be the probability that \(i, j\) will establish communication during session \(S = (t_0, t^M]\) given \((\mathcal{A}, \Gamma_0)\).

Let \(\mathcal{C}\) be the class of oracles \(\mathcal{A}\) for which the outdegree \(d_t\) is set equal to \(v\) for all nodes \(i\) in \(G_t\) and for all instances \(t\).

**Proposition 5.1.** The response time of Algorithm 1 increases with increased requests to communication.

**Proof.** The probability that a specific process is chosen in the ASK or RESPOND phases decreases monotonically with the number of processes to which the process executing ASK or RESPOND is willing to communicate. 

By Proposition 5.1, the class of oracles \(\mathcal{C}\) gives an upper bound in the response time of the system, since adding requests to communicate cannot decrease the response time.

**Corollary 5.1.** For oracles \(\mathcal{A} \in \mathcal{C}\), \(c_{ij}(\mathcal{A}, \Gamma_0) < 1/v\) for the nonpreferential Algorithm 1.
Consider the event $E = \{\text{process } i \text{ is in the responding phase in the interval } \Delta_i = [t_i(t), t_i(t+2)] \text{ and process } j \text{ is in the same asking phase and waiting in a watching window for } i, \text{ for at least } (v/2)c_R \text{ steps of process } i \text{ during } \Delta_i\}$. Let $x_{ij}(\mathcal{A}, \Gamma_{t_0}, E)$ be the probability that $i,j$ will establish communication during session $S = (t_0, t_m]$, given $(\mathcal{A}, \Gamma_{t_0})$ and event $E$.

**Proposition 5.2.**

$$x_{ij}(\mathcal{A}, \Gamma_{t_0}, E) \cdot \text{Prob}(E \text{ given } (\mathcal{A}, \Gamma_{t_0})) \leq \delta_{ij}(\mathcal{A}, \Gamma_{t_0}) .$$

(Proof easy).

Note that for both algorithms the following holds:

**Proposition 5.3.**

$$x_{ij}(\mathcal{A}, \Gamma_{t_0}, E) > 1 - (1 - \frac{1}{v})^{v/2} > 1 - e^{-1/2} ,$$

since given $E$, it is enough for $i$ to select $j$ as the process to answer for at least one of the at least $\frac{v}{2}$ consecutive answering intervals which overlap with the watching window of $j$.

**Theorem 5.1.** For Algorithm 1, we have

$$\text{Prob}(E \text{ given } (\mathcal{A}, \Gamma_{t_0})) \geq \frac{1}{4v} .$$

**Proof.** The length of a watching window of $j$ is $c_B = c_R \cdot (m-l)$ steps of $j$, which is at least $c_R \cdot (m-l) \cdot r_{\min}$ time, which is at least

$$c_R \cdot (m-l) r_{\min} \cdot \frac{1}{r_{\max}} \geq c_R (v+3)$$

steps of $i$. 
Let $A_\tau = \{t_1, t_2\}$. The interval $A_\tau$ either contains at least half of a phase $A_j$ of $j$, or half of it is contained in a phase $A_j$ of $j$. (See Figure 3). In either case, given that $j$ is asking $i$ during $A_j$ and that $i$ is responding during $A_\tau$, there is an overlap of the watching window of the phase $A_j$ of $j$ and of phase $A_\tau$ of $i$ which contains at least $c \cdot \frac{v}{R}$ steps of $i$. Since both phases $A_j$ and $A_\tau$ were selected in the session $S$ after $t_0$, during probability of $j$ asking $i$ during $A_j$ is $\geq 1/2v$ and the probability of $i$ answering during $A_\tau$ is $1/2$. Our theorem follows by multiplying these probabilities.\[\square\]

**THEOREM 5.2.** For Algorithm 2, we have

$$\text{Prob}(E \text{ given } (A, t_0)) \geq \frac{1}{4}.$$  

**Proof.** Same as in 5.1. The only difference is that now $j$ insists on asking $i$ and hence $\text{prob}(j \text{ asking } i \text{ given } j \text{ in asking phase and preferring } i) = 1.$ \[\square\]

Let

$$c_{\text{min}} = \frac{1}{4v} (1 - e^{-1/2}), \quad c_{\text{max}} = \frac{1}{v} \quad \text{for Algorithm 1}$$

and

$$c_{\text{min}} = \frac{1}{4} (1 - e^{-1/2}), \quad c_{\text{max}} = 1 \quad \text{for Algorithm 2}.$$  

**THEOREM 5.3.**

$$0 < c_{\text{min}} \leq c_{ij}(A, t_0) \leq c_{\text{max}} < 1.$$

**Proof.** By Theorems 5.1, 5.2, Propositions 5.2 and 5.3 and Corollary 5.1. \[\square\]
Note that our lower bounds on \(x_{ij}(\mathcal{A}, \Gamma_t, t_0)\) and \(\text{prob}(E \text{ given } \mathcal{A}, \Gamma_t, t_0)\) do not depend on \(\mathcal{A}\) or \(\Gamma_t\). This is so because all inequalities hold for any possible speed ratio of processes \(i, j\) and because the results of choices of phases for times \(t \geq t_m\) in session \(S\) do not depend on \(\mathcal{A}\) or \(\Gamma_t\).

Let \(P_{ij}(k|\mathcal{A}, \Gamma_t, t_0)\) be the probability it takes exactly \(k\) sessions for processes \(i, j\) to succeed in establishing communication, given that \(i \triangleleft j\) (or \(i \triangleleft j\) and \(j \triangleleft i\)) for a time interval \(\Delta\) starting at \(t_0\), such that \(\Delta \leq 1\).

Let \(S_0 = t_0, S_1, \ldots, S_{k-1}\) be the starting times of these sessions.

Then, by Baye's formula,

\[
P_{ij}(k|\mathcal{A}, \Gamma_t, t_0) = (1 - \sigma_{ij}(\mathcal{A}, S_0)) \cdot (1 - \sigma_{ij}(\mathcal{A}, S_1)) \cdot \ldots \cdot (1 - \sigma_{ij}(\mathcal{A}, S_{k-2})) \cdot \sigma_{ij}(\mathcal{A}, S_{k-1})
\]

Since for all \(\mathcal{A}\), all \(\Gamma_t\)

\[
\sigma_{\min} \leq \sigma_{ij}(\mathcal{A}, \Gamma_t) \leq \sigma_{\max}
\]

we have

\[
P_{ij}(k|\mathcal{A}, \Gamma_t, t_0) \leq \sigma_{\max} (1 - \sigma_{\min})^{k-1}
\]

and

\[
P_{ij}(k|\mathcal{A}, \Gamma_t, t_0) \geq \sigma_{\min} (1 - \sigma_{\max})^{k-1}
\]

By using the above inequalities and calculating the mean, we get

**LEMMA 5.1.**

\[
\frac{\sigma_{\min}}{(\sigma_{\max})^2} \leq \text{mean}(k) \leq \frac{\sigma_{\max}}{(\sigma_{\min})^2}
\]
and, by known expressions about tails of geometrics, we get

**Lemma 5.2.** \( \forall \varepsilon, \ 0 < \varepsilon < 1, \)

\[ \text{Prob}\{k > k_{\max}(\varepsilon)\} < \varepsilon \]

where

\[ k_{\max}(\varepsilon) = \frac{\log((\sigma_{\min}/\sigma_{\max})/\omega)}{\log(1-\sigma_{\min})}. \]

Recall \( 3c_v \) is an upper bound on a session length. Lemmas 5.1 and 5.2 imply

**Theorem 5.4.** If \( \tau \) is the response of the system, then

\[ \text{mean}(\tau) < 3c_v \cdot \frac{\sigma_{\max}}{\sigma_{\min}} \]

and if \( \tau(\varepsilon) \) is the \( \varepsilon \)-error response, then

\[ \tau(\varepsilon) < 3c_v \cdot k_{\max}. \]

By using \( c = \left(1 + \frac{3}{v}\right)\frac{\sigma_{\max}}{\sigma_{\min}} \cdot c_R \) and the \( \sigma_{\max}, \sigma_{\min} \) of Theorems 5.1 and 5.2, we get

**Corollary 5.1.** For Algorithm 1

\[ \text{mean}(\tau) \leq 48(1-e^{-1/2})^{-2} \cdot (r_{\max}/r_{\min})^2 \cdot (1 + \frac{3}{v}) \cdot v^2 \]

or

\[ \text{mean}(\tau) = O(v^2) \]

and

\[ k_{\max}(\varepsilon) = \frac{\log\left(\frac{\varepsilon}{4} \cdot (1-e^{-1/2})\right)}{\log\left(1 - \frac{1}{4v} \cdot (1-e^{-1/2})\right)} = O\left(v \log\left(\frac{4}{\varepsilon}\right)\right) \]

implying
\[
\tau(\varepsilon) \leq 3c_{\max} \cdot k_{\max}(\varepsilon) = O\left(\varepsilon^2 \log\left(\frac{4}{\varepsilon}\right)\right).
\]

Also, by using the derived \(c_{\min}, c_{\max}\) for Algorithm 2 we get

**COROLLARY 5.2.** For Algorithm 2,

\[
\text{mean}(\tau) \leq 48(1-e^{-1/2})^{-2}.\left(\frac{r_{\max}}{r_{\min}}\right) \cdot c_{R} \cdot \left(1 + \frac{3}{v}\right) \cdot v = O(v)
\]

and

\[
k_{\max}(\varepsilon) = \frac{\log\left(\frac{\varepsilon}{4} \cdot (1-e^{-1/2})\right)}{\log\left(1 - \frac{1}{4} \cdot (1-e^{-1/2})\right)} = O\left(\log\left(\frac{4}{\varepsilon}\right)\right)
\]

implying

\[
\tau(\varepsilon) = O\left(v \log\left(\frac{4}{\varepsilon}\right)\right).
\]

6. **CONCLUSION**

We have provided two real time implementations for the DCS system. A key assumption on our time analysis is that processes have to be tame during attempts to communicate, but at other times processes need not be tame. This improves a previous version of this paper [Reif, Spirakis, 1981A], where we required processes to be tame at all times.

A referee has suggested a modification of our algorithms which may be of practical use in speeding up the expected time response in some practical cases. The modification presumes that the connections graph has fixed valence (otherwise, an infinite number of variables per process is required). The idea is to allow each process to have additional flag
variables which indicate to other processes its willingness to communicate with them. (We had presumed that the set $E_i$ can only be read by process $i$), so the idea requires additional flag variables. Those modified algorithms will have worst case performance identical to those given in our paper.

In a further paper, [Reif, Spirakis, 1982], we have relaxed our assumption of tameness. In that paper we require only bounds on the relative acceleration of ratios of speeds of neighbor processes. We propose there synchronization algorithms which have relative real time response, where communication is established with high probability between any pair of processes within constant number of steps of the slowest process. However, these algorithms are less efficient than those given in this paper. Also, in the Appendix of [Reif, Spirakis, 1982], we are applying our synchronization techniques to ADA for a relative real time implementation.

Acknowledgments

The authors wish to thank Ed Clarke, who introduced us to the synchronization problems considered in this paper, and Michael Rabin, whose previous work in probabilistic synchronization inspired this work. Stavros Macrakis is thanked for helpful comments on our real time CSP implementation. Also, the referees made many very useful comments.
References


APPENDIX
A REAL-TIME IMPLEMENTATION OF CSP

[Hoare, 1978] introduced a concurrent programming language CSP (for Communicating Sequential Processes). The CSP language is notable for the elegance of its synchronization constructs: They are powerful and yet simple. [Bernstein, 1980] describes an extension of CSP which allows both input command and output commands as guards. Here we briefly describe CSP with Bernstein's extension and present a real-time implementation of the synchronization constructs.

CSP Synchronization Constructs

The relevant aspects of CSP concern its process structure and communication mechanisms. Concurrent execution of processes \( P_1, P_2, \ldots, P_n \) is denoted

\[
[P_1 \parallel P_2 \parallel \ldots \parallel P_n]
\]

Each process has its own set of variables which are inaccessible to all other processes. The communication primitives are the output command

\( P_j ! u \)

that requests that \( P_j \) receive the value of \( u \) and input command

\( P_i ? x \)

which requests that \( P_i \) send a value which is then assigned to \( x \).

There are two relevant compound statements. The alternative statement

\[
[G_1 = C_1 \iff G_2 = C_2 \iff \ldots \iff G_k = C_k]
\]
contains guards $G_1, \ldots, G_k$ and command lists $C_1, \ldots, C_k$. Each guard consists of a list of elements which may be a sequence of booleans, followed by at most one input command or (in Bernstein's extension of CSP) an output command.

The execution nondeterminately chooses a guard $G_i$ which is satisfied (to test that, it executes each element of $G_i$ from left to right) and then executes the corresponding command list $C_i$. If no guard is satisfied, the alternative statement fails. The repetitive statement

$$e_0[G_1 + C_1 + \cdots + G_k + C_k]$$

results in the repeated execution of the alternative statement

$$[G_1 + C_1 + \cdots + G_k + C_k]$$

until no guards are satisfied.

Note that the crucial problem in implementing CSP is to synchronize executions of input commands $P_j ? x$ by process $P_i$ with output commands $P_i ! u$ by process $P_j$ so that the value $u$ is transmitted to $x$.

It is very easy to implement CSP by DCS. (In fact, this was the original motivation for our work on DCS). Let $\varepsilon$ be a system-wide constant, which may be fixed to any arbitrarily small constant on the interval $(0,1)$. We assume a real-time DCS implementation with $\varepsilon$-error response time $T(\varepsilon)$.

Let $v$ be the maximum number of guards appearing in any alternative or repetitive statement; we assume that $v$ is constant relative to the total number $n$ of processes. We also assume that the length of the guard lists is bounded by a small fixed constant. We also assume all processes reliably execute their programs and satisfy assumptions A1 and A2.

Our CSP implementation is real-time in the sense that there exists a positive integer $I$ (which is independent of the number of processes $n$) such that if in some alternative or repetitive statement $e$ some guard $G$
is continuously satisfied for a time interval $\Delta$ of length $\gg \ell$ and if the processes of $G$ and the process executing the statement are tame on $\Delta$, then the command list associated with some satisfied guard is immediately executed with probability $\geq 1-\varepsilon$ and otherwise, a failure exit is always made immediately after a time interval of length $\ell$. Therefore, we allow a failure exit with probability $<\varepsilon$, even though some guard may be satisfied.

To attempt to execute an output command $P_j u$ in process $P_i$, $P_i$ sets $P_i \rightarrow P_j$, indicating $P_i$ is willing to communicate with $P_j$. Also, to attempt to execute an input command $P_i x$ in process $P_j$, $P_j$ sets $P_j \rightarrow P_i$. If successful communication is established by $P_i$ and $P_j$, the process $P_j$ immediately transmits value $u$ to variable $x$ in $P_i$; and immediately thereafter $P_i$ sets $P_i \leftrightarrow P_j$ and $P_j$ sets $P_j \leftrightarrow P_i$.

An alternative or repetitive statement $S$ may contain the execution of one of several guarded input commands and output commands, say $G_1, \ldots, G_s$ where $s \ll v$. To execute the statement $S$, $P_i$ first executes the booleans appearing in each guard. Let $R$ be the set of processes appearing in those guards of $S$ all of whose booleans evaluate to true. $P_i$ must set $P_i \rightarrow P_j$ for each $P_j \in R$ for a time interval of length $\ell = \tau(\varepsilon)$. At the first time that an appropriate communication is established between $P_i$ and some willing process $P_j \in R$, $P_i$ must immediately set $P_i \leftrightarrow P_j$, for all $P_j \in R$ and then $P_i$ must execute the command list associated with the now satisfied guard in the statement $S$. Otherwise, if no appropriate communication is established within time $\tau(\varepsilon)$, $P_i$ must then exit the statement $S$ with failure. Note that the probability of an incorrect failure exit is $<\varepsilon$. 
Figure 1A. The connections graph $H$ in the case of a ring network of five processes.
Figure 1B. The willingness digraph $G_t$
Figure 1C. The open-channel graph $M_t$. 
Figure 2. A session $S$ of $i,j$ and one of the possible orderings of events.

*: indicates the start of a phase

$\Delta_j$ is a phase of $j$

$\Delta_i$ is a phase of $i$
Figure 3A. A case of phase overlap where phase $\Delta_i$ of $i$ contains at least half of the phase $\Delta_j$ of $j$. 
Figure 3B. Phase $\Delta_j$ of $j$ contains at least half of phase $\Delta_i$ of $i$. 