How to Implement a Time-Free Perfect Failure Detector in Partially Synchronous Systems

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***Abstract*— This paper[1] shows how to implement a time-free perfect failure detector in a partially synchronous distributed system. Rather than upper and lower bounds on the minimum and maximum end-to-end computation + transmission delays between correct processors, our algorithm needs to know only an upper bound on their ratio. Since this bound may still hold when an assumed bound on the maximum delay is violated, our perfect failure detector may still work correctly in situations where synchronous ones fail, i.e., has higher coverage. We prove that our solution, which employs heartbeat messages and a timer-free "timeout" mechanism based upon synchronized heartbeat rounds, indeed satisfies the properties of a perfect failure detector and provides a number of attractive features.**

Keywords: Fault-tolerant distributed systems, perfect failure detectors, partially synchronous system models, consistent broadcasting, real-time scheduling, queueing systems, coverage.

I. Introduction

It has been taken for granted for many years that fault-tolerant distributed *real-time* computing problems admit solutions designed in synchronous computational models only. Unfortunately, given the difficulty of ensuring that stipulated bounds on computation times and transmission delays are always met (which is notoriously difficult with many systems, especially those built out of COTS products), the safety/liveness/timeliness properties achieved with such systems may have a poor coverage.[2] This holds true for any design that rests upon (some) timed semantics, including timed asynchronous systems [1] and the Timely Computing Base [2]. With such solutions, the core question is: How do you set your timers?

Some safety and liveness properties, like agreement in consensus, can be guaranteed in purely asynchronous computational models, however. Since asynchronous algorithms do not depend upon timing assumptions, those properties hold regardless of the underlying system's actual timing conditions. The coverage of such time-free solutions is hence necessarily higher than that of a solution involving some timing assumptions.

The apparent contradiction between time-free algorithms and timeliness properties can be resolved by adhering to the *design immersion* principle, which was introduced in [3] and referred to as the *late binding* principle in [4]. Design immersion permits to consider time-free (pure asynchronous) algorithms for implementing high-level services in real-time systems, by enforcing that timing-related conditions (like "delay for time X") are expressed as time-free logical conditions (like "delay for x round-trips"). Safety and liveness properties can

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[2]The coverage of an assertion is the probability or the likelihood that this assertion holds true in some given universe. Coverage is hence the central issue in many systems, critical systems in particular.

hence be proved *independently* of the timing properties of the system where the time-free algorithm will eventually be run. Timeliness properties are established only late in the design process, by conducting a worst-case schedulability analysis, when a time-free solution is immersed in a real system with its specific low-level timing properties.

Given that many important problems in fault-tolerant distributed computing do not have deterministic solutions in the purely asynchronous model [5], the latter must be enriched with some additional semantics for circumventing impossibility results. In order to achieve some very high coverage, such added semantics should be *time-free*. The present paper explores the following fundamental theoretical and practical question: Is there a *time-free* solution for implementing a powerful time-free semantics? Such a solution could be proved correct independently of the timing properties of the system where it is eventually run, and just immersed into the system to be fielded as any other time-free design.

Our paper answers this fundamental question in the affirmative, by providing a time-free design of a perfect failure detector $\mathcal{P}$ [6]. It is based upon a new partially synchronous system model, refered to as the Θ-model, which stipulates a bounded end-to-end computational + transmission delay ratio Θ only. Since our solution does not incorporate any bound on delays, and works even in situations where actual delays are unbounded, our Θ-model effectively allows us to escape from both the impossibility of implementing $\mathcal{P}$ in presence of *unknown* delay bounds of [7] and the impossibility of consensus in presence of *unbounded* delays of [8]. Consequently, the numerous failure detector-based distributed algorithms developed during the last decade can be used for building real-time systems with a coverage that cannot be met by existing synchronous solutions.

The remaining sections are organized as follows: Following a detailed relation to existing work in Section II, we introduce a simple queueing system model of a distributed system in Section III. The latter will help us to justify the Θ-model presented in Section IV. Section V introduces the basic operation principle of our novel design for implementing $\mathcal{P}$. The detailed algorithm is presented and proved correct in Section VI. A number of extensions of our approach in Section VII eventually conclude our paper.

II. Problem Description and Related Work

Failure detectors (FD's) [6] were introduced in the context of asynchronous systems with crash failures. They consist of a set of (low level) modules, one per processor, which can be queried locally by the higher level processes in order to obtain information about which processors have crashed. This information neither needs to be always correct nor consistent at different processors. It must be in accordance with some axiomatic (time-free) FD specification, however, which is usually made up of two parts: *Completeness*, addressing an FD's ability to correctly suspect crashed processors, and *accuracy*, addressing an FD's ability not to incorrectly suspect non-crashed processors.

Several classes of FD specifications have been introduced in [6], which differ primarily in their accuracy requirements. The strongest one is the *perfect failure detector* $\mathcal{P}$, defined by

(SC) *Strong completeness*: Eventually, every processor that crashes is permanently suspected by every correct processor.

(SA) *Strong accuracy*: No processor is suspected before it crashes.

It has been shown in [6] and in the wealth of subsequent work that most problems in fault-tolerant distributed computing, such as consensus, atomic broadcast or leader election, can be solved in systems where $\mathcal{P}$ (even some weaker FD) is implementable. Note that this requires at least a partially synchronous system model, since an implementation of $\mathcal{P}$ in a purely asynchronous system would contradict [5].

Any work on partially synchronous systems we are aware of assumes that delay bounds are either known, see e.g. [9], [10], or are unknown but finite and can hence be learned during the execution via "incremental" timeouts [11]. It has in fact been shown in [8] that consensus—and hence $\mathcal{P}$—cannot be implemented in systems where just one process could crash if either processing or communication delays are unbounded.

The seminal paper [11] classifies partial synchrony according to whether bounds upon the maximum relative processing speeds (Φ) and the maximum absolute communication delays (Δ) exist but are either unknown, or are known but hold only after some unknown *global stabilization time* GST. Those two models were combined into a single generalized partially synchronous model in [6]. It assumes that relative speeds, delays and message losses are arbitrary up to GST; after GST, no message may be lost and all relative speeds and all communication delays must be smaller than the unknown upper bounds Φ and Δ, respectively. This model underlies most

research on failure detectors.

Since *perpetual* FDs cannot be implemented in partially synchronous systems with unknown delay bounds [6], [11], see [7], perpetual accuracy properties like *strong accuracy* ("no processor is suspected before it crashes") are usually replaced by *eventual* ones ("there is a time after which correct processors are not suspected by any correct processor"). Many papers deal with the implementation of such eventual-type FDs [6], [12]–[24], and we will survey some of their core ideas below. We note, however, that eventual properties are in conflict with the timeliness requirements of real-time systems: The algorithms running atop of an eventual-type FD are usually guaranteed to terminate only after the FD becomes perfect.

In [6], a simple implementation of an eventually perfect failure detector $\diamond\mathcal{P}$ for the generalized partially synchronous model was given. It is based upon monitoring periodic "I am alive"-messages using adaptive (increasing) timeouts at all receiver processors. Starting from an a priori given initial value, the timeout value is increased every time a false suspicion is detected (which occurs when an "I am alive"-message from a suspected processor drops in). By restricting the recipients of "I am alive"-messages from all processors to suitably chosen subsets, a less costly implementation of an eventually strong failure detector $\diamond\mathcal{S}$ was derived in [17].

Alternative FD implementations, which use polling by means of ping/reply roundtrips instead of "I am alive"-messages, have also been proposed for partially synchronous systems. The message-efficient algorithms of [15] use a logical ring, where processors poll only their neighbors and use an adaptive (increasing) timeout for generating suspicions. A similar technique is used in the adaptive failure detection protocol implementing $\diamond\mathcal{P}$ in systems with finite average delays [21]. It uses piggybacking of FD messages upon application messages in order to reduce the message load.

A major deficiency of most existing adaptive timeout approaches is their inability to also decrease the timeout value, cp. [17]. Obviously, such solutions cannot adapt to (slowly) varying delays over time. Stochastic delay estimation techniques as in [18], [22] could be used if one accepts decreased performance w.r.t. accuracy. QoS aspects—as well as scalability and overall system load—in a probabilistic framework are also addressed in [20].

A different type of unreliable failure detectors that received considerable attention recently is Ω, which outputs just a single—eventually common—processor that is considered up and running. Ω also allows to solve consensus [14] and can be implemented very efficiently even in partially synchronous systems where only some links eventually respect communication delay bounds [23].

In purely asynchronous systems, it is impossible to implement even eventual-type failure detectors. FDs with very weak specifications [13], [19] have been proposed as an alternative here. The *heartbeat failure detectors* of [19] do not output a list of suspects but rather a list of unbounded counters. Like $\diamond\mathcal{P}$, they permit to solve the important problem of quiescent reliable communication in the presence of crashes, but unlike $\diamond\mathcal{P}$, they can easily be implemented in purely asynchronous systems.

In view of the impossibility results of [8] and [7], it was taken for granted until recently that implementing perpetual failure detectors requires accurate knowledge of delay bounds and hence a synchronous system model. Still, the algorithms presented in [24] reveal that perpetual FDs can be implemented in a time-free manner in systems with specific properties. For example, there is a time-free implementation of $\mathcal{P}$ in systems where it can be *assumed a priori* that every correct processor is connected to a set of $f+1$ processors via links that are not among their f slowest ones. The algorithm cannot verify whether the underlying system actually satisfies this assumption, however, and no design for implementing this property was given.

In [4], we showed that the problem of implementing perpetual failure detectors in a synchronous system comprising n processors initially can be stated as a generic real-time scheduling problem. A *fast failure detector* algorithm was given as a function of x, which serves to dynamically recompute timeout values. It implements FDs Ω, $\mathcal{S}$, or $\mathcal{P}$, by assigning x value 1, s, or n, respectively, where s is the smallest number of stable processors that cannot be suspected unless they fail. The proposed FD achieves very low detection time [18], [25] by exploiting the fact that failure detection can be separated from the application (i.e., the atop running consensus algorithm). The failure detector service can in fact be run as a low-level service implemented as high-priority processes, which exchange high-priority FD-level messages scheduled according to some head-of-the-line policy. As a consequence, *fast failure detectors* admit an accurate worst-case schedulability analysis, which provides tight bounds on the (inherently small) end-to-end delay of FD-level messages.

III. Queueing System Model

We consider a distributed system of n processors, which are fully interconnected by perfect links. There is no need to specify a particular failure model for this section; we will just assume that up to $0 \leq f \leq n-1$ processors may be faulty in some way. Let δ_{pq} denote the end-to-end computational + transmission delay required for assembly, transmission and processing of any FD-level message sent from some correct processor p to some correct processor q. Note that δ_{pq} includes any computation of the distributed (failure detector) algorithm at both p and q as well.

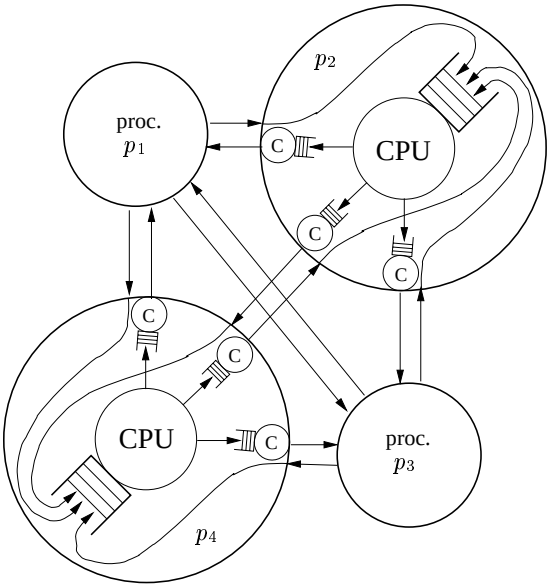

Fig. 1. *A simple queueing system representation of a fully connected distributed system of 4 processors.*

In real systems, δ_{pq} consists not only of physical data transmission and processing times. Rather, *queueing delays* due to the inevitable *scheduling* of the concurrent execution of multiple processes and message arrival interrupts/threads on every processor must be added to the picture. Fig. 1 shows a simple queueing system model of a fully connected distributed system: All messages that drop in over one of the $n-1$ incoming links of a processor must eventually be processed by the single CPU. Every message that arrives while the CPU processes former ones must hence be put into the CPU queue for later processing. In addition, all messages produced by the CPU must be scheduled for transmission over every outgoing link. Messages that find an outgoing link busy must hence be put into the send queue of the link's communication controller for later transmission.

Consequently, the end-to-end delay $\delta_{pq} = d_{pq} + \omega_{pq}$ between sender p and receiver q actually consists of a "fixed" part d_{pq} and a "variable" part ω_{pq}. The fixed part $d_{pq} > 0$ is solely determined by the processing speeds of p and q and the data transmission characteristics (distance, speed, etc.) of the interconnecting link. It determines the minimal conceivable δ_{pq} and is easily determined from the physical characteristics of the system. The real challenge is the variable part $\omega_{pq} \geq 0$, however, which captures all scheduling-related variations of the end-to-end delay:

- Precedences, resource sharing and contention, with or without resource preemption, which creates waiting queues,
- Varying (application-induced) load,
- Varying process execution times (which may depend on actual values of process variables and message contents),
- Occurrence of failures.

It is apparent that ω_{pq} and thus δ_{pq} depend critically upon (1) the scheduling strategy employed (determining which message is put at which place in a queue), and (2) the particular distributed algorithm(s) executed in the system: If the usual FIFO scheduling is replaced by head-of-the-line scheduling favoring FD-level messages and computations over all application-level ones, for example, the variability of ω_{pq} at the FD-level can be decreased by orders of magnitude, see [4] and Table I. That the queue sizes and hence the end-to-end delays δ_{pq} increase with the number and processing requirements of the messages sent by the particular distributed algorithm that is run atop of the system is immediately evident.

The above queueing system model thus reveals that the popular synchronous and partially synchronous models rest upon a very strong assumption: That an a priori given upper bound[3] $\overline{\tau}^{+} \geq \delta_{pq}$ exists, which is—as part of the model—essentially independent of the particular algorithm. In reality, such a bound can only be determined by a detailed *worst-case schedulability analysis*[4] [26], [27]. In order to deal with all the causes of delays listed above, this schedulability analysis requires complete knowledge of the underlying system, the scheduling strategies, the

[3]Overbars are used for stipulated (= a priori known) bounds on actual (= unknown) values.

[4]Measurement-based approaches are a posteriori solutions. Asserting a priori knowledge of an upper bound implies predictability, which is achievable only via worst-case schedulability analyses. With measurement-based approaches, the actual bounds remain unknown (even "a posteriori"), which might suffice for non-critical systems, but is out of question with safety-critical systems.

failure model and, last but not least, the particular algorithms that are to be executed in the system. Compiling $\overline{\tau}+$ into the latter algorithms, as required by solutions that rest upon timing assumptions, hence generates a cyclic dependency. Moreover, conducting any detailed worst-case schedulability analysis is notoriously difficult. Almost inevitably, it rests on simplified models of reality (environments, technology) that may not always hold. As a consequence, $\overline{\tau}^+$ and hence any non time-free solution's basic assumptions might be violated at run time in certain situations.

IV. Θ-Model

In this section, we briefly introduce our Θ-model and argue why it makes sense. Lacking space does not allow us to incorporate a detailed relation to existing models and an in-depth analysis of its coverage here, however. They will be provided in a forthcoming paper.

The following Definition 1 captures the essentials of our Θ-model.

Definition 1 (Θ-Model): For any execution E of a distributed algorithm $\mathcal{A}$ under some failure model $\mathcal{F}$, let $\tau^-(t)$ resp. $\tau^+(t)$, with uncertainty $\varepsilon(t) = \tau^+(t) - \tau^-(t)$, be the minimum resp. maximum end-to-end computational + transmission delay of the messages in some subset $M(t)$ of all the messages in transit by real-time t in execution E. The system must be such that the delay ratio $\Theta(t) = \tau^+(t)/\tau^-(t)$ respects a given[5] upper bound $\overline{\Theta}$ for any execution E.

The set $M(t)$ in Definition 1 connects system model, failure model, and the particular distributed algorithm under study, which cannot be completely independent of each other according to Section III. Typically, $M(t)$ consists of messages exchanged by correct processors that are in transit in a short time window—of duration $O(\tau^+(t))$—around t. Refer to Section VI for the definition of $M(t)$ in case of our failure detector.

Obviously, we assume that the algorithm does not know $\tau^+(t)$, $\tau^-(t)$ and $\Theta(t)$: Only $\overline{\Theta}$ may be compiled into its code. Still, we will use $\tau^+(t) \equiv \tau^+$, $\tau^-(t) \equiv \tau^-$ and $\Theta(t) \equiv \Theta$ for all t as (unevaluated) variables in our analysis. Note carefully that they are considered constant, i.e., time-invariant, here in order to simplify our arguments. It can be shown, however, that this simplified analysis is also sufficient for dealing with the time-varying case: By introducing a suitably defined notion of "stretched" real-time $t' = g(t)$, time-varying quantities w.r.t. t can be transformed in constant quantities w.r.t. t'. The inverse function $g^{[-1]}(t')$ may then be used to translate the results back to the real-time domain t again.

The actual value of $\overline{\Theta}$, which obviously depends upon many system parameters, can only be determined by a detailed schedulability analysis. Typical values reported for $\overline{\Theta}$ in real-time systems research [28], [29] are $2 \ldots 10$. To get an idea of how $\Theta(t)$ behaves in a real system, we conducted some experiments on a network of Linux workstations running our FD algorithm. A custom monitoring software was used to determine bounds $\overline{\tau}^- \leq \tau^-(t)$ and $\overline{\tau}^+ \geq \tau^+(t)$ as well as $\overline{\Theta} \geq \Theta(t)$ under a variety of operating conditions. The FD algorithm was run at the application level (AL-FD), as an ordinary Linux process, and as a fast failure detector (F-FD) using high-priority threads and head-of-the-line scheduling [4]. Table I shows some measurement data for 5 machines (with at most $f = 1$ arbitrary faulty one) under low (5 % network load) and medium (0–60 % network load, varying in steps) application-induced load. Additional data will be provided in a forthcoming paper.

FD	**Load**	τ^- (μs)	τ^+ (μs)	Θ	$\frac{\tau^+}{\tau^-} : \Theta$
AL-FD	low	55	15080	228.1	1.20
F-FD	low	54	648	9.5	1.26
F-FD	med	56	780	10.9	1.27

TABLE I

Some typical experimental data from a small network of Linux workstations running our FD algorithm.

In the remainder of this section, we will argue why the Θ-model has higher coverage in real systems than existing synchronous and partially synchronous models. First of all, we note that the time-variance of $\tau^+(t)$ and $\tau^-(t)$ rules out a straightforward approach for simulating a synchronous system in the Θ-model: One could try to determine an upper bound $\overline{\tau}^+ = \overline{\Theta} \cdot t_{rt}/2$ on the end-to-end delays δ_{pq} by using just a single (correct) round-trip delay measurement t_{rt}, which must of course satisfy $t_{rt} \geq 2\tau^-$. The bound $\overline{\tau}+$ computed via this approach is not necessarily valid at the future time t when it is computed and used, however, since it is based upon a round-trip taken at some past time $t' < t$. Hence, in general, it is impossible to reliably compute a message timeout value for some future real-time t out of present measurements at time $t' < t$.

As far as its relation to synchronous and partially synchronous computing models is concerned, the Θ-model is obviously weaker than the synchronous model with

[5]There are variants of the Θ-model where $\overline{\Theta}$ is unknown, or known but holds after some unknown GST, as in [6], [11].

upper bound $\overline{\tau}^+$. After all, τ^+ may exceed any $\overline{\tau}^+$ in cases of overload without violating $\Theta \leq \overline{\Theta}$, provided that τ^- goes up as well. As we will argue below, this is likely or even certain to be true, depending on the particular system under consideration. Similarly, the Θ-model is weaker than the partially synchronous model of [11]: The latter model stipulates a ratio Φ for computational speeds but also needs a (known or unknown) upper bound Δ on *absolute* communication delays. Since Δ includes the queueing delays ω_{pq} introduced in Section III, τ^+ and hence Δ need not be bounded when Θ is bounded.

Still, both the standard synchronous model (with lower bound $\overline{\tau}^- = 0$) and the above partially synchronous model are weaker than the Θ-model w.r.t. the lower bound: Assuming $\overline{\tau}^- = 0$ has of course higher coverage than assuming some $\overline{\tau}^- > 0$ as required for $\Theta < \infty$. We argue, however, that the assumption $\overline{\tau}^- = 0$ is overly conservative and may be dropped without loosing signigicant coverage. In fact. $\overline{\tau}^- > 0$ can be determined by means of a *best-case schedulability analysis* [29], [30], which relies upon the best case scenario for the end-to-end delays. Since this involves ideal conditions, in particular, no queueing delays, $\overline{\tau}^-$ is typically easily determined with a coverage close to 1 via the physical properties of processors and transmission links. Moreover, from a theoretical perspective, stipulating $\overline{\tau}^- = 0$ is equivalent to assuming infinite processing an networking speeds. In this case, $\overline{\tau}^+ = 0$ as well.

It follows that, under strictly equivalent assumptions, the coverage of the Θ-model is as least as high as the coverage of the corresponding synchronous and partially synchronous models. If there is just *one* load/failure scenario where $\tau^+ > \overline{\tau}^+$ but still $\Theta \leq \overline{\Theta}$ holds, its coverage is in fact higher. Of course, the real gain in coverage depends upon the particular system considered and can only be determined by a detailed coverage analysis. Below we explain why (possibly significant) gains in coverage may be expected.

Our experimental data reveal that a considerable correlation between $\tau^+(t)$ and $\tau^-(t)$ indeed exists: The last column in Table I shows that $\overline{\Theta}$ is nearly 30 % smaller than $\overline{\tau}^+/\overline{\tau}^-$. Hence, when τ^+ increases, τ^- goes up to some extent as well. Note that τ^- must in fact only increase by α/Θ to compensate some $\tau^+ + \alpha$ here. This correlation can be explained as follows.

First of all, the set $M(t)$ typically restricts τ^+, τ^- to messages exchanged between *correct* processes. If, say, $\delta_{xy} > \tau^+$ for less than f processes x and/or y, this can be attributed to process timing failures and is hence tolerated transparently by proper fault-tolerant algorithms. An actual violation of τ^+ is hence a phenomenon that must occur in a significantly large part of the system, which makes it likely that it affects every processor to some extent. For certain types of networks, like broadcast buses, this is even a certainty. Note that this hypothesis is also supported by our experimental data, which reveal that the correlation between τ^+ and τ^- increases when f is increased.

Consequently, if $\delta_{pq} = \tau^+ > \overline{\tau}^+$ occurs at some processor pair p, q due to an increasing application-induced load in some significant portion of a system that employs "fully distributed" algorithms (as opposed to leader-based ones) like our FD, additional messages are generated and sent to all processors in the system. They will hence populate the CPU queue at every processor in Fig. 1. Even if the computations of interest are the highest-priority ones and messages are transmitted using head-of-the-line policies, it may well be the case that this high-load situation does not allow the (often quite unlikely per se) best-case scenario $\delta_{rs} = \tau^-$ to occur at some processor pair s, r simultaneously: In fact, τ^- usually assumes that no blocking of high-priority processes by non-preemptable operations like sending a low-priority message occurs, which becomes increasingly difficult to maintain if the number of such messages increases. Consequently, the ratio of maximum over minimum delay need not grow as fast (if at all) as the maximum delay when the load increases.

Given such correlations between minimum and maximum end-to-end delays, the probability of violating $\overline{\Theta}$ is indeed smaller than the probability of violating $\overline{\tau}^+$. Consequently, Θ-based designs like the failure detector of Section V indeed surpass synchronous solutions in terms of coverage here.

V. Principle of Operation

In this section, we introduce the principle of operation of our time-free perfect failure detector, which is based upon the consistent broadcasting primitive of [31]. Consistent broadcasting is implemented by means of two functions, *broadcast* and *accept*, which can be used to trigger a nearly simultaneous global event in the system: For example, a processor executing the clock synchronization algorithm of [31] (see Fig. 2) invokes *broadcast* to signal that it is ready for the resynchronization event to happen. It waits for the occurrence of this resynchronization event by calling *accept*, where it blocks until the event happens. The detailed semantics of consistent broadcasting is captured by three properties,

namely, correctness, unforgeability and relay, which are defined as follows:

Definition 2 (Consistent Broadcasting Properties):

(C) *Correctness*: If at least $f+1$ correct processors call *broadcast* by time t, then *accept* is unblocked at every correct processor by time $t + \tau^+_{rt}$, for some $\tau^+_{rt} \geq 0$.

(U) *Unforgeability*: If no correct processor calls *broadcast* by time t, then *accept* cannot unblock at any correct processor by $t + \tau^-_{rt}$ or earlier, for some $\tau^-_{rt} \geq 0$.

(R) *Relay*: If *accept* is unblocked at a correct processor at time t, then every correct processor does so by time $t + \tau_\Delta$, for some $\tau_\Delta \geq 0$.

Implementations of consistent broadcasting, providing specific values of τ^+_{rt}, τ^-_{rt} and τ_Δ, can be found in [32], [33].

Now consider a very simple algorithm, which executes infinitely many instances of consistent broadcasting $R = 0, 1, \ldots$ in direct[6] succession: If *broadcast*$_0$ is called by sufficiently many processors, *accept*$_0$ will eventually unblock and trigger *broadcast*$_1$, which in turn starts the same sequence for instance $1, \ldots$ Let σ^R_p denote the time when instance R terminates, that is, *accept*$_R$ unblocks and *broadcast*$_{R+1}$ starts at processor p. It is easy to show that the following holds for this algorithm:

Lemma 1 (Consecutive Consistent Broadcasting): Let $R \geq P \geq 0$ be two arbitrary instances of successive consecutive consistent broadcasting. Then,

$$|\sigma^R_p - \sigma^R_q| \leq \tau_\Delta \quad (1)$$

$$\sigma^R_p - \sigma^P_q \geq (R-P)\tau^-_{rt} - \tau_\Delta \quad (2)$$

$$\sigma^R_p - \sigma^P_q \leq (R-P)\tau^+_{rt} + \tau_\Delta \quad (3)$$

for any two correct processors p, q.

Proof: Equation (1) follows immediately from the relay property (R), which establishes (2) and (3) for $P = R$ as well. We can hence assume that (2) holds for $k - 1 = R - P - 1 \geq 0$ and have to show that it holds for $k = R - P$ as well. Since processor p unblocks *accept*$_R$ at time σ^R_p, at least one non-faulty processor p_1 must have called *broadcast*$_R$ by time $\sigma^R_p - \tau^-_{rt}$ by the unforgeability property (U) of consistent broadcasting. Hence $\sigma^R_p - \sigma^{R-1}_{p_1} \geq \tau^-_{rt}$. By the induction hypothesis, we have $\sigma^{R-1}_{p_1} - \sigma^P_q \geq (R-P-1)\tau^-_{rt} - \tau_\Delta$, from which (2) follows immediately by adding up.

[6]To reduce the system load caused by FD messages, some delay could of course be introduced in between, see [33].

For the upper bound, we can assume that (3) holds for $k - 1 = R - P - 1 \geq 0$ and have to show that it holds for $k = R - P$ as well. Since we know that even the last correct processor unblocks *accept*$_{R-1}$ at some time $\sigma^{R-1}_{\max}$ satisfying $\sigma^{R-1}_{\max} - \sigma^P_q \leq (R-P-1)\tau^+_{rt} + \tau_\Delta$ by the induction hypothesis, it follows from the correctness property (C) of consistent broadcasting that processor p must unblock *accept*$_R$ by time $\sigma^{R-1}_{\max} + \tau^+_{rt}$, from where (3) follows again by adding up. □

Equipped with this result, we can make the following important observation: Let us extend our simple successive consistent broadcasting algorithm by additionally broadcasting an $R+1$-*heartbeat* message (containing $R+1$ as data) when calling *broadcast*$_{R+1}$ at every processor. Now consider some correct processor p at time σ^R_p (when it sends its $R+1$-heartbeat): If p did not see a $P+1$-heartbeat, $P \leq R$, from some processor q (which should have been sent at time σ^P_q) by time σ^R_p, it must be the case that this heartbeat travels longer than $\sigma^R_p - \sigma^P_q \geq (R-P)\tau^-_{rt} - \tau_\Delta$ according to (2). Since we assumed that a heartbeat from a correct processor takes at most τ^+ to arrive, choosing

$$\Xi = R - P \geq \frac{\tau^+ + \tau_\Delta}{\tau^-_{rt}} \quad (4)$$

such that $\tau^+ \leq \Xi\tau^-_{rt} - \tau_\Delta$ ensures that p cannot miss q's $P+1$-heartbeat if q is correct. So if p did not see the $P+1$-heartbeat from q by time σ^R_p, q must have crashed and can safely be put on the list of suspects at processor p.

Of course, as it appears in (4), Ξ depends upon τ^+ and cannot be computed if this value is unknown. Our detailed analysis of consistent broadcasting in [32], [33] reveals, however, that actually $\tau^-_{rt} = 2\tau^-$ and $\tau_\Delta = 2\tau^+ - \tau^-$. Plugging this into our expression for Ξ yields $\Xi \geq 1.5\tau^+/\tau^- - 0.5$, i.e., a value that *only depends upon the ratio* $\Theta = \tau^+/\tau^-$. If an upper bound $\overline{\Theta}$ on Θ was known, we could compute Ξ even when bounds $\overline{\tau}^+$ and $\overline{\tau}^-$ on τ^+ and τ^-, respectively, are unknown! Recall that neither $\overline{\tau}^+$ nor $\overline{\tau}^-$ are built into our algorithm's code.

To further illustrate this important issue, we discuss an alternative implementation of $\mathcal{P}$, which works only in synchronous systems. The alternative algorithm is based upon the simple fact that consistent broadcasting allows to implement approximately synchronized clocks [31]. Each processor p must be equipped with a clock device $C_p(t)$ for this purpose, which is used to implement round R's clock $C^R_p(t) = C_p(t) + c^{R-1}_p$, by choosing

a suitable time offset c_p^{R-1} set by the clock synchronization algorithm in round $R-1$. Note that we stipulate a round -1 clock $C_p^{-1}(t) = C_p(t)$ to be used in round 0. A single "composite" clock $C'_p(t)$ that equals the round clocks at the respective round switching times can be implemented atop of this, see [31, Sec. 7] for details.

Fig. 2 shows the simple clock synchronization algorithm of [31], which concurrently executes one instance of consistent broadcasting per resynchronization round R. Invoking *broadcast*$_R$ indicates that the calling processor is ready to resynchronize and hence starts resynchronization round R, which is done every D seconds. Note carefully that the period D measures time according to every processor's clock, hence is a parameter of the algorithm that must assume some specific value. Consistent broadcasting ensures nearly simultaneous unblocking of *accept*$_R$—and hence resynchronization—of all non-faulty processors within τ_Δ by the relay property (R). A suitably chosen offset α is used to ensure that a clock is never set backwards.

Processor $R \geq 0$*:*
if $C^{R-1}(t) = R \cdot D$ /* ready to start C^R */
  $\rightarrow$ *broadcast*$_R$;
fi if *accept*$_R$
  $\rightarrow C^R(t) := R \cdot D + \alpha$; /* resynchronize */
fi

Fig. 2. *A clock synchronization algorithm based upon consistent broadcasting*

The proof of correctness of this algorithm only depends upon the properties of consistent broadcasting. A detailed analysis in [31], [32] yields the following worst-case synchronization precision of the composite clock $C'_p(t)$:

$$\pi_{\max} = [(D-\alpha)(1+\rho) + \tau_{rt}^+]dr + \tau_\Delta(1+\rho) + \alpha, \quad (5)$$

where ρ is the worst-case clock drift and $dr = \rho(2+\rho)/(1+\rho)$.

In order to implement a failure detector, it suffices to add the same $R+1$-heartbeat broadcast as before when *broadcast*$_{R+1}$ is called. Obviously, processor q's $P+1$-heartbeat is sent at time $(P+1)D$ on q's clock, when processor p's clock reads at most $(P+1)D+\pi_{\max}$. When this heartbeat does not arrive by the time processor p performs *broadcast*$_{R+1}$, i.e., at time $(R+1)D$ on p's clock, q must have crashed if $\Xi = R-P$ is chosen such that $(R-P)D - \pi_{\max} \geq \tau^+$ (assuming clock drift $\rho = 0$ for simplicity). With $\alpha = 0$ and $D = \tau_{rt}^-$ as the minimal conceivable[7] choice of D, we find $\pi_{\max} = \tau_\Delta$ and hence

$$\Xi = R - P \geq \frac{\tau^+ + \tau_\Delta}{\tau_{rt}^-} \quad (6)$$

exactly as in (4). Consequently, both the algorithm of Fig. 4 and the one based upon Fig. 2 can (ideally) achieve approximately the same detection time. However, apart from the fact that the correctness of the above algorithm depends upon the correct operation of a processor's clock, it also needs the parameter D for properly adjusting the periodic *broadcasts*. In order to ensure that the computed precision $\pi_{\max}$ according to (5) is valid, D must be sufficiently large to ensure that any instance of consistent broadcasting is completed before the next one starts, which implies $D \geq 2\tau^+$. Therefore, the failure detector built atop of the algorithm in Fig. 2 is not time-free and may fail if τ^+ increases beyond the limit set forth by the choice of D.

VI. A Timer-Free Failure Detector

As explained in Section V, our failure detector implementation uses consistent broadcasting for implementing a time- and timer-free timeout mechanism based upon approximately synchronized rounds. Fig. 3 shows an implementation of the pivotal consecutive consistent broadcasting primitive, which works in presence of at most f arbitrary processor failures[8] if $n \geq 3f+1$. It has been derived from [31, Fig. 2] by simply replacing "*accept*" with "*broadcast*$_{R+1}$", which immediately starts the next instance.

Note carefully that all instances $R = 0, 1, \ldots$ of our algorithm must be created at boot time, in order to be ready when started by their predecessors. Again, σ_p^R denotes the time when round $R+1$ is started by *broadcast*$_{R+1}$.

By extending the proof of [31, Thm. 5], it is not difficult to show that the above algorithm satisfies the properties of consistent broadcasting in our system model.

[7]Those settings are smaller than the ones required by the analysis in [31], but serve as a means to illustrate the smallest conceivable lower bound on $R-P$ only.

[8]The classic perfect failure detector specification is of course only meaningful for simple crash failures. The existing work on muteness detector specifications [12], [16], [34]–[36] suggests to consider also more severe types of failures, however. Note also that there is a simpler implementation for f omission faulty processors, which only needs $n \geq 2f+1$ [31]. We use the more demanding version here, since it also tolerates arbitrary processor timing failures, i.e., f processors that inconsistently emit apparently correct messages at arbitrary times. An even more advanced hybrid version of consistent broadcasting, which tolerates hybrid processor and link failures, can be found in [33].

```
Implementation of broadcast_R:
    send (init, R) to all;

Code for process R:
cobegin
/* Concurrent block 1 */
if received (init, R) from f + 1 distinct processors
    → send (echo, R) to all [once]; /* sufficient evidence */
fi
/* Concurrent block 2 */
if received (echo, R) from f + 1 distinct processors
    → send (echo, R) to all [once]; /* sufficient evidence */
fi
if received (echo, R) from 2f + 1 distinct processors
    → broadcast_{R+1}; /* start next instance */
fi
coend
```

Fig. 3. *A simple consecutive consistent broadcasting algorithm*

Theorem 1 (Consistent Broadcasting Properties): In a system with $n \geq 3f + 1$ processors, where at most f may be arbitrary faulty during the entire execution, the consistent broadcasting primitive of Fig. 3 created at boot time guarantees the properties of Definition 2 with $\tau_{rt}^{+} = 2\tau^{+}$, $\tau_{rt}^{-} = 2\tau^{-}$, and $\tau_{\Delta} = \varepsilon + \tau^{+} \leq \tau_{rt}^{+}$. System-wide, at most $2n$ broadcasts of $(1+\log_2 C_R)$-bit messages are performed by non-faulty processors, where C_R denotes the cardinality of the round number space (for R).

Proof: See [33] (or [32]). □

Figure 3 allows us to briefly describe the set of messages $M(t)$ used in Definition 1 in case of our failure detector. As explained in Section V, our FD exploits the fact that the fastest message that could have contributed to processor p's round switching at time σ_p^R must have had a delay of at least $\tau^{-} = \tau^{+}/\Theta \geq \tau^{+}/\overline{\Theta}$, provided that some heartbeat message with delay at least τ^{+} is in transit at time σ_p^R. $M(t)$ is hence essentially the set of FD-level messages $T_R(\sigma_p^R)$ in transit between correct processes at time $t = \sigma_p^R$. More specifically, if δ_{qp} denotes the $f+1$-shortest delay of an (echo, R) message from some process q (correct or not) sent to p that contributed to round switching, $M(\sigma_p^R)$ consists of this message and all messages in $T_R(\sigma_p^R)$ with delay at least δ_{qp}. Note that this also removes the typically very small self-reception delay δ_{pp}. A similar definition of $M(t)$ is used for time $t = \rho_p^R$, where (echo, R) is emitted by processor p. Otherwise, $M(t) = \emptyset$.

We note, however, that $\overline{\Theta}$ resulting from this simple definition of $M(t)$ is overly conservative: Using a slightly more refined analysis[9] that is based upon Θ and $\Theta_f = \tau^{+}/\tau_f^{-}$, where τ_f^{-} is the $f+1$-shortest message delay between correct processes, the $2f+1$-shortest-delay (echo, R) messages sent to p by some processor can be used instead of the $f+1$-shortest one for constructing $M(\sigma_p^R)$. The real $\overline{\Theta}$ for our FD is hence considerably smaller.

From Section V, we know that we only have to add the heartbeat-broadcast and the suspicion technique to the algorithm in Fig. 3 to get our timer-free failure detector as given in Fig. 4. Fortunately, we can simply use the (init, R) message as a processor's R-*heartbeat* message, since it is emitted at the time σ_p^{R-1} when *broadcast*$_R$ is started.

```
Global variables:
    suspect[∀q] :=false; /* list of suspected processors */
    saw_max[∀q] := 0; /* maximum heartbeat seen */

Implementation start_R: /* Start heartbeat round R */
    send (init, R) to all;

Code process R:
cobegin
/* Concurrent block 1 */
if received (init, R) from q
    → if R > saw_max[q]
        → saw_max[q] := R; /* saw new heartbeat */
      fi
fi
if received (init, R) from f + 1 distinct processors
    → send (echo, R) to all [once]; /* sufficient evidence */
fi
/* Concurrent block 2 */
if received (echo, R) from f + 1 distinct processors
    → send (echo, R) to all [once]; /* sufficient evidence */
fi
if received (echo, R) from 2f + 1 distinct processors
    → ∀q: if R + 1 − Ξ > saw_max[q]
            → suspect[q] :=true; /* q has crashed */
          fi
      start_{R+1}; /* Start next heartbeat round */
fi
coend
```

Fig. 4. *Our time-free perfect failure detector algorithm*

The following major Theorem 2 shows that the algorithm of Fig. 4 indeed implements a perfect failure detector in partially synchronous systems where only $\overline{\Theta} \geq \Theta = \tau^{+}/\tau^{-}$ is known. Recall that it is only the classic specification of the perfect failure detector $\mathcal{P}$ that forces us to consider crash failures; our implementation works even in presence of arbitrary faulty processors.

[9]Or, preferably, by employing an alternative implementation of consistent broadcasting.

Theorem 2 (Failure Detector Properties): Let Ξ be an integer with $\Xi \geq \lceil (3\overline{\Theta} - 1)/2 \rceil$. In a system with $n \geq 3f+1$ processors, the algorithm given in Fig. 4 with all processes created at boot time implements a perfect failure detector with detection time at most $2(\Xi+2)\tau^+ - \tau^-$. During $C_R \geq 1$ rounds, every correct processor has running time within $[(2C_R+1)\tau^- - 2\tau^+, 2(C_R+1)\tau^+ - \tau^-]$ and broadcasts at most $2n$ messages of size at most $(1 + \log_2 C_R)$ bits per round system-wide.

Proof: We have to show that the properties (SC) and (SA) of a perfect failure detector, given in Section II, are satisfied.

As far as strong accuracy (SA) is concerned, we use the argument developed in Section V. It confirms that every correct processor p gets the $P+1$-heartbeat of any alive processor q by the time σ_p^R when p emits its $R+1$-heartbeat, provided that Ξ is chosen according to (4). This evaluates to

$$\Xi \geq \frac{\tau^+ + \tau_\Delta}{\tau_{rt}^-} = \frac{3\tau^+ - \tau^-}{2\tau^-} = \frac{3\Theta - 1}{2} \qquad (7)$$

according to the latencies of consistent broadcasting given in Theorem 1. Inequality (7) obviously holds when Ξ is chosen as stated in our theorem.

As far as strong completeness is concerned, it is obvious that a processor q that has crashed stops emitting heartbeats. Hence, eventually, every alive processor recognizes that the expected heartbeat is missing and suspects q. The worst case for detection time occurs if a processor q crashes immediately after broadcasting its P-heartbeat, for some $P > 0$, at time σ_q^{P-1}. At time σ_p^R with $R - P = \Xi$, processor p recognizes that the $P+1$-heartbeat from q (which should have been emitted at time σ_q^P) is missing. According to (3) in Lemma 1, the detection time must hence be less than

$$\sigma_p^R - \sigma_q^{P-1} \leq (\Xi+1)\tau_{rt}^+ + \tau_\Delta = 2(\Xi+2)\tau^+ - \tau^-$$

according to Theorem 1 as asserted.

The bounds for the algorithm's running time for C_R rounds are determined by the running times of consistent broadcasting, hence follow immediately from (2) and (3) in conjunction with Theorem 1. The number of messages broadcast (= "send to all") and the message complexity follows immediately from Theorem 1. □

Remarks:

1) In the presence of crash (and even omission) failures, our failure detector guarantees that the properties (SC) and (SA) are maintained at all processors, i.e., even at faulty processors, until they crash. This is due to the fact that Theorem 1 is actually *uniform* [37], i.e., holds for such processors as well.
2) The algorithm does not need to know n, except for the size of the suspect list.
3) Initializing saw_max$[\forall q] := 0$ in Fig. 4 ensures that the very first 0-heartbeat is not used for suspecting a processor. This must be avoided, since we cannot assume that all correct processors start their execution within τ_Δ (which would be required to extend Lemma 1 to $R = -1$).
4) A theoretical disadvantage of our solution is that the message size is unbounded since it incorporates R. However, solutions to this problem—construction of a bounded round numbering scheme—are known, given that Ξ is known.

As a final remark, we note that the perfect failure detector algorithm of Fig. 4 could easily be transformed into an eventually perfect failure detector $\diamond\mathcal{P}$ that works also when Θ is unknown but finite, possibly after some unknown GST. All that needs to be done here is to increment Ξ every time a message from a suspected processor drops in later.

VII. Conclusions

In this paper, we showed how to implement a time- and timer-free perfect failure detector $\mathcal{P}$. The partially synchronous Θ-model utilized in our analysis requires a bound $\overline{\Theta}$ on the ratio $\Theta = \tau^+/\tau^-$ of maximum vs. minimum end-to-end delays only. Since there are systems or/and conditions where $\overline{\Theta} \geq \Theta$ holds true even when some stipulated upper bound $\overline{\tau}^+$ is violated (due to overloads, failure occurrences, etc.), our implementation of $\mathcal{P}$ achieves a coverage that is higher than what can be expected with synchronous solutions. Using the design immersion principle, our FD hence allows to build high-coverage distributed real-time systems based upon time-free (asynchronous) algorithms.

This result has important theoretical as well as practical implications. First, our FD works in a partially synchronous system where delay bounds are unknown, apparently contradicting [7]. Second, as discussed in Section IV, Θ may remain bounded even when τ^+ exceeds some assumed bound $\overline{\tau}^+$. In other words, there are conditions under which the correctness of our solution for implementing $\mathcal{P}$ does not depend upon load assumptions, apparently contradicting [8] as well.

The apparent contradictions are due to the fact that both [7] and [8] consider τ^- and τ^+ to be uncorrelated. For example, it can be assumed in [7] that the time

t until correct suspicion in the strong completeness property (SC) is independent of τ^+, since the latter is unknown. This is not true if $\overline{\Theta}$ is known, however, since our FD can infer something about the maximum delay τ^+ of messages still in transit from already received messages via $\overline{\Theta}$. Hence, an unknown upper bound upon the transmission delay alone is not sufficient to cause the impossibility result to apply. A similar argument applies for the impossibility of consensus in case of unbounded delays [8].

Part of our current/future work in this area is devoted to several extensions of our approach. In [33], we show how to arbitrarily reduce Ξ and system load by introducing additional delays, and how to deal with hybrid processor and link timing/value failures according to our perception-based failure model [38]. In [39], we present an alternative FD implementation based upon clock synchronization in the Θ-model [40], which also improves Ξ and allows us to get rid of the simultaneous booting assumption. We also found out that other problems in asynchronous distributed computing, like the SDD problem [41] related to atomic commitment, can be solved in the Θ-model.

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