Formalization of a Generalized Protocol for Clock Synchronization in Isabelle/HOL

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Abstract

We formalize the generalized Byzantine fault-tolerant clock synchronization protocol of Schneider. This protocol abstracts from particular algorithms or implementations for clock synchronization. This abstraction includes several assumptions on the behaviors of physical clocks and on general properties of concrete algorithms/implementations. Based on these assumptions the correctness of the protocol is proved by Schneider. His proof was later verified by Shankar using the theorem prover EHDM (precursor to PVS). Our formalization in Isabelle/HOL is based on Shankar's formalization.

Contents

1 Introduction

In certain distributed systems, e.g., real-time process-control systems, the existence of a reliable global time source is critical in ensuring the correct functioning of the systems. This reliable global time source can be implemented using several physical clocks distributed on different nodes in the distributed system. Since physical clocks are by nature constantly drifting away from the "real time" and different clocks can have different drift rates, in such a scheme, it is important that these clocks are regularly adjusted so that they are closely synchronized within a certain application-specific safe bound. The design and verification of clock synchronization protocols are often complicated by the additional requirement that the protocols should work correctly under certain types of errors, e.g., failure of some clocks, error in communication network or corrupted messages, etc.

There has been a number of fault-tolerant clock synchronization algorithms studied in the literature, e.g., the *Interactive Convergence Algorithm* (ICA) by Lamport and Melliar-Smith [1], the Lundelius-Lynch algorithm [2], etc., each with its own degree of fault tolerance. One important property that

must be satisfied by a clock synchronization algorithm is the agreement property, i.e., at any time t, the difference of the clock readings of any two non-faulty processes must be bounded by a constant (which is fixed according to the domain of applications). At the core of these algorithms is the convergence function that calculates the adjustment to a clock of a process, based on the clock readings of all other processes. Schneider [3] gives an abstract characterization of a wide range of clock synchronization algorithms (based on the convergence functions used) and proves the agreement property in this abstract framework. Schneider's proof was later verified by Shankar [4] in the theorem prover EHDM (precursor to PVS), where eleven axioms about clocks are explicitly stated.

We formalize Schneider's proof in Isabelle/HOL, making use of Shankar's formulation of the clock axioms. The particular formulation of axioms on clock conditions and the statements of the main theorems here are essentially those of Shankar's [4], with some minor changes in syntax. For the full description of the protocol, the general structure of the proof and the meaning of the constants and function symbols used in this formalization, we refer readers to [4].

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2 Isar proof scripts

theory *GenClock* **imports** *Complex-Main* **begin**

2.1 Types and constants definitions

Process is represented by natural numbers. The type 'event' corresponds to synchronization rounds.

type-synonym *process* = *nat*
type-synonym *event* = *nat*
type-synonym *time* = *real*
type-synonym *Clocktime* = *real*

axiomatization
  δ :: *real* **and**
  μ :: *real* **and**
  ϱ :: *real* **and**
  rmin :: *real* **and**
  rmax :: *real* **and**
  β :: *real* **and**
  Λ :: *real* **and**

  np :: *process* **and**
  maxfaults :: *process* **and**

  PC :: [*process*, *time*] $\Rightarrow$ *Clocktime* **and**

  VC :: [*process*, *time*] $\Rightarrow$ *Clocktime* **and**

  te :: [*process*, *event*] $\Rightarrow$ *time* **and**

ϑ :: [*process*, *event*] $\Rightarrow$ (*process* $\Rightarrow$ *Clocktime*) **and**

IC :: [*process*, *event*, *time*] $\Rightarrow$ *Clocktime* **and**

correct :: [*process*, *time*] $\Rightarrow$ *bool* **and**

cfn :: [*process*, (*process* $\Rightarrow$ *Clocktime*)] $\Rightarrow$ *Clocktime* **and**

π :: [*Clocktime*, *Clocktime*] $\Rightarrow$ *Clocktime* **and**

α :: *Clocktime* $\Rightarrow$ *Clocktime*

definition
count :: [*process* $\Rightarrow$ *bool*, *process*] $\Rightarrow$ *nat* **where**
count f n = *card* $\{p.\ p < n \wedge f\ p\}$

definition

Adj :: [*process*, *event*] $\Rightarrow$ *Clocktime* **where**
Adj = (λ *p i. if 0 < i then cfn p* (ϑ *p i*) − *PC p* (*te p i*)
else 0)

definition

okRead1 :: [*process* $\Rightarrow$ *Clocktime*, *Clocktime*, *process* $\Rightarrow$ *bool*] $\Rightarrow$ *bool* **where**
okRead1 f x ppred $\longleftrightarrow$ ($\forall$ *l m. ppred l* $\wedge$ *ppred m* $\longrightarrow$ $|f\ l - f\ m| \leq x$)

definition
okRead2 :: [*process* $\Rightarrow$ *Clocktime*, *process* $\Rightarrow$ *Clocktime*, *Clocktime*,
process $\Rightarrow$ *bool*] $\Rightarrow$ *bool* **where**
okRead2 f g x ppred $\longleftrightarrow$ ($\forall$ *p. ppred p* $\longrightarrow$ $|f\ p - g\ p| \leq x$)

definition
rho-bound1 :: [[*process*, *time*] $\Rightarrow$ *Clocktime*] $\Rightarrow$ *bool* **where**
rho-bound1 C $\longleftrightarrow$ ($\forall$ *p s t. correct p t* $\wedge$ $s \leq t \longrightarrow C\ p\ t - C\ p\ s \leq (t - s)*(1 + \varrho)$)
definition
rho-bound2 :: [[*process*, *time*] $\Rightarrow$ *Clocktime*] $\Rightarrow$ *bool* **where**
rho-bound2 C $\longleftrightarrow$ ($\forall$ *p s t. correct p t* $\wedge$ $s \leq t \longrightarrow (t - s)*(1 - \varrho) \leq C\ p\ t - C\ p\ s$)

2.2 Clock conditions

Some general assumptions

axiomatization where
constants-ax: $0 < \beta \wedge 0 < \mu \wedge 0 < rmin$
$\wedge\ rmin \leq rmax \wedge 0 < \varrho \wedge 0 < np \wedge maxfaults \leq np$

axiomatization where
PC-monotone: $\forall$ *p s t. correct p t* $\wedge$ $s \leq t \longrightarrow PC\ p\ s \leq PC\ p\ t$

axiomatization where
VClock: $\forall$ *p t i. correct p t* $\wedge$ $te\ p\ i \leq t \wedge t < te\ p\ (i + 1) \longrightarrow VC\ p\ t = IC\ p\ i\ t$

axiomatization where
IClock: $\forall\ p\ t\ i.\ correct\ p\ t \longrightarrow IC\ p\ i\ t = PC\ p\ t + Adj\ p\ i$

Condition 1: initial skew

axiomatization where
init: $\forall\ p.\ correct\ p\ 0 \longrightarrow 0 \leq PC\ p\ 0 \wedge PC\ p\ 0 \leq \mu$

Condition 2: bounded drift

axiomatization where
rate-1: $\forall\ p\ s\ t.\ correct\ p\ t \wedge s \leq t \longrightarrow PC\ p\ t - PC\ p\ s \leq (t - s)*(1 + \varrho)$ **and**
rate-2: $\forall\ p\ s\ t.\ correct\ p\ t \wedge s \leq t \longrightarrow (t - s)*(1 - \varrho) \leq PC\ p\ t - PC\ p\ s$

Condition 3: bounded interval

axiomatization where
rts0: $\forall\ p\ t\ i.\ correct\ p\ t \wedge t \leq te\ p\ (i+1) \longrightarrow t - te\ p\ i \leq rmax$ **and**
rts1: $\forall\ p\ t\ i.\ correct\ p\ t \wedge te\ p\ (i+1) \leq t \longrightarrow rmin \leq t - te\ p\ i$

Condition 4 : bounded delay

axiomatization where
rts2a: $\forall\ p\ q\ t\ i.\ correct\ p\ t \wedge correct\ q\ t \wedge te\ q\ i + \beta \leq t \longrightarrow te\ p\ i \leq t$ **and**
rts2b: $\forall\ p\ q\ i.\ correct\ p\ (te\ p\ i) \wedge correct\ q\ (te\ q\ i) \longrightarrow abs(te\ p\ i - te\ q\ i) \leq \beta$

Condition 5: initial synchronization

axiomatization where
synch0: $\forall\ p.\ te\ p\ 0 = 0$

Condition 6: nonoverlap

axiomatization where
nonoverlap: $\beta \leq rmin$

Condition 7: reading errors

axiomatization where
readerror: $\forall\ p\ q\ i.\ correct\ p\ (te\ p\ (i+1)) \wedge correct\ q\ (te\ p\ (i+1)) \longrightarrow$
$abs(\vartheta\ p\ (i+1)\ q - IC\ q\ i\ (te\ p\ (i+1))) \leq \Lambda$

Condition 8: bounded faults

axiomatization where
correct-closed: $\forall\ p\ s\ t.\ s \leq t \wedge correct\ p\ t \longrightarrow correct\ p\ s$ **and**
correct-count: $\forall\ t.\ np - maxfaults \leq count\ (\lambda\ p.\ correct\ p\ t)\ np$

Condition 9: Translation invariance

axiomatization where
trans-inv: $\forall\ p\ f\ x.\ 0 \leq x \longrightarrow cfn\ p\ (\lambda\ y.\ f\ y + x) = cfn\ p\ f + x$

Condition 10: precision enhancement

axiomatization where
prec-enh:
$\forall\ ppred\ p\ q\ f\ g\ x\ y.$
$np - maxfaults \leq count\ ppred\ np \wedge$
$okRead1\ f\ y\ ppred \wedge okRead1\ g\ y\ ppred \wedge$

$okRead2\ f\ g\ x\ ppred \wedge ppred\ p \wedge ppred\ q$
$\longrightarrow abs(cfn\ p\ f - cfn\ q\ g) \leq \pi\ x\ y$

Condition 11: accuracy preservation

axiomatization where
acc-prsv:
$\forall\ ppred\ p\ q\ f\ x.\ okRead1\ f\ x\ ppred \wedge np - maxfaults \leq count\ ppred\ np$
$\wedge\ ppred\ p \wedge ppred\ q \longrightarrow abs(cfn\ p\ f - f\ q) \leq \alpha\ x$

2.2.1 Some derived properties of clocks

lemma *rts0d*:
assumes *cp*: $correct\ p\ (te\ p\ (i+1))$
shows $te\ p\ (i+1) - te\ p\ i \leq rmax$
using *cp rts0* **by** *simp*

lemma *rts1d*:
assumes *cp*: $correct\ p\ (te\ p\ (i+1))$
shows $rmin \leq te\ p\ (i+1) - te\ p\ i$
using *cp rts1* **by** *simp*

lemma *rte*:
assumes *cp*: $correct\ p\ (te\ p\ (i+1))$
shows $te\ p\ i \leq te\ p\ (i+1)$
proof−
  from *cp rts1d* **have** $rmin \leq te\ p\ (i+1) - te\ p\ i$
    by *simp*
  from *this constants-ax* **show** *?thesis* **by** *arith*
qed

lemma *beta-bound1*:
assumes *corr-p*: $correct\ p\ (te\ p\ (i+1))$
and *corr-q*: $correct\ q\ (te\ p\ (i+1))$
shows $0 \leq te\ p\ (i+1) - te\ q\ i$
proof−
  from *corr-p rte* **have** $te\ p\ i \leq te\ p\ (i+1)$
    by *simp*
  from *this corr-p correct-closed* **have** *corr-pi*: $correct\ p\ (te\ p\ i)$
    by *blast*
  from *corr-p rts1d nonoverlap* **have** $rmin \leq te\ p\ (i+1) - te\ p\ i$
    by *simp*
  from *this nonoverlap* **have** $\beta \leq te\ p\ (i+1) - te\ p\ i$ **by** *simp*
  hence $te\ p\ i + \beta \leq te\ p\ (i+1)$ **by** *simp*

  from *this corr-p corr-q rts2a*
  have $te\ q\ i \leq te\ p\ (i+1)$
    by *blast*
  thus *?thesis* **by** *simp*
qed

lemma *beta-bound2*:
assumes *corr-p*: $correct\ p\ (te\ p\ (i+1))$
and *corr-q*: $correct\ q\ (te\ q\ i)$

```
shows te p (i+1) − te q i ≤ rmax + β
proof−
  from corr-p rte have te p i ≤ te p (i+1)
    by simp
  from this corr-p correct-closed have corr-pi: correct p (te p i)
    by blast

  have split: te p (i+1) − te q i =
    (te p (i+1) − te p i) + (te p i − te q i)
    by (simp)

  from corr-q corr-pi rts2b have Eq1: abs(te p i − te q i) ≤ β
    by simp
  have Eq2: te p i − te q i ≤ β
  proof cases
    assume te q i ≤ te p i
    from this Eq1 show ?thesis
      by (simp add: abs-if)
  next
    assume ¬ (te q i ≤ te p i)
    from this Eq1 show ?thesis
      by (simp add: abs-if)
  qed

  from corr-p rts0d have te p (i+1) − te p i ≤ rmax
    by simp
  from this split Eq2 show ?thesis by simp
qed
```

2.2.2 Bounded-drift for logical clocks (IC)

```
lemma bd:
  assumes ie: s ≤ t
  and rb1: rho-bound1 C
  and rb2: rho-bound2 D
  and PC-ie: D q t − D q s ≤ C p t − C p s
  and corr-p: correct p t
  and corr-q: correct q t
  shows | C p t − D q t |  ≤ | C p s − D q s | + 2∗ϱ∗(t − s)
proof−
  let ?Dt = C p t − D q t
  let ?Ds = C p s − D q s
  let ?Bp = C p t − C p s
  let ?Bq = D q t − D q s
  let ?I = t − s

  have | ?Bp − ?Bq | ≤ 2∗ϱ∗(t − s)
  proof−
    from PC-ie have Eq1: | ?Bp − ?Bq | = ?Bp − ?Bq by (simp add: abs-if)
    from corr-p ie rb1 have Eq2: ?Bp − ?Bq ≤ ?I∗(1+ϱ) − ?Bq (is ?E1 ≤ ?E2)
      by(simp add: rho-bound1-def)
    from corr-q ie rb2 have ?I∗(1 − ϱ) ≤ ?Bq
      by(simp add: rho-bound2-def)
```

```
    from this have Eq3: ?E2 ≤ ?I∗(1+ϱ) − ?I∗(1 − ϱ)
      by(simp)
    have Eq4: ?I∗(1+ϱ) − ?I∗(1 − ϱ) = 2∗ϱ∗?I
      by(simp add: algebra-simps)
    from Eq1 Eq2 Eq3 Eq4 show ?thesis by simp
  qed
  moreover
  have |?Dt| ≤ |?Bp − ?Bq| + |?Ds|
    by(simp add: abs-if)
  ultimately show ?thesis by simp
qed

lemma bounded-drift:
  assumes ie: s ≤ t
  and rb1: rho-bound1 C
  and rb2: rho-bound2 C
  and rb3: rho-bound1 D
  and rb4: rho-bound2 D
  and corr-p: correct p t
  and corr-q: correct q t
  shows |C p t − D q t| ≤ |C p s − D q s| + 2∗ϱ∗(t − s)
proof−
  let ?Bp = C p t − C p s
  let ?Bq = D q t − D q s

  show ?thesis
  proof cases
    assume ?Bq ≤ ?Bp
    from this ie rb1 rb4 corr-p corr-q bd show ?thesis by simp
  next
    assume ¬ (?Bq ≤ ?Bp)
    hence ?Bp ≤ ?Bq by simp
    from this ie rb2 rb3 corr-p corr-q bd
    have |D q t − C p t| ≤ |D q s − C p s| + 2∗ϱ∗(t − s)
      by simp
    from this show ?thesis by (simp add: abs-minus-commute)
  qed
qed
```

Drift rate of logical clocks

```
lemma IC-rate1:
rho-bound1 (λ p t. IC p i t)
proof−
  {
    fix p::process
    fix s::time
    fix t::time
    assume cp: correct p t
    assume ie: s ≤ t
    from cp ie correct-closed have cps: correct p s
      by blast
    have IC p i t − IC p i s ≤ (t − s)∗(1+ϱ)
    proof−
```

```
      from cp IClock have IC p i t = PC p t + Adj p i
        by simp
      moreover
      from cps IClock have IC p i s = PC p s + Adj p i
        by simp
      moreover
      from cp ie rate-1 have PC p t − PC p s ≤ (t − s)∗(1+ϱ)
        by simp
      ultimately show ?thesis by simp
    qed
  }
  thus ?thesis by (simp add: rho-bound1-def)
qed

lemma IC-rate2:
rho-bound2 (λ p t. IC p i t)
proof−
  {
    fix p::process
    fix s::time
    fix t::time
    assume cp: correct p t
    assume ie: s ≤ t
    from cp ie correct-closed have cps: correct p s
      by blast
    have (t − s)∗(1 − ϱ) ≤ IC p i t − IC p i s
    proof−
      from cp IClock have IC p i t = PC p t + Adj p i
        by simp
      moreover
      from cps IClock have IC p i s = PC p s + Adj p i
        by simp
      moreover
      from cp ie rate-2 have (t − s)∗(1−ϱ) ≤ PC p t − PC p s
        by simp
      ultimately show ?thesis by simp
    qed
  }
  thus ?thesis by (simp add: rho-bound2-def)
qed
```

Auxilary function *ICf*: we introduce this to avoid some unification problem in some tactic of isabelle.

```
definition
  ICf :: nat ⇒ (process ⇒ time ⇒ Clocktime) where
  ICf i = (λ p t. IC p i t)

lemma IC-bd:
  assumes ie: s ≤ t
  and corr-p: correct p t
  and corr-q: correct q t
  shows |IC p i t − IC q j t| ≤ |IC p i s − IC q j s| + 2∗ϱ∗(t − s)
proof−
  let ?C = ICf i
```

```
  let ?D = ICf j
  let ?G = |?C p t − ?D q t| ≤ |?C p s − ?D q s| + 2∗ϱ∗(t − s)

  from IC-rate1 have rb1: rho-bound1 (ICf i) ∧ rho-bound1 (ICf j)
    by (simp add: ICf-def)

  from IC-rate2 have rb2: rho-bound2 (ICf i) ∧ rho-bound2 (ICf j)
    by (simp add: ICf-def)

  from ie rb1 rb2 corr-p corr-q bounded-drift
  have ?G by simp

  from this show ?thesis by (simp add: ICf-def)
qed

lemma event-bound:
assumes ie1: 0 ≤ (t::real)
and corr-p: correct p t
and corr-q: correct q t
shows ∃ i. t < max (te p i) (te q i)
proof (rule ccontr)
  assume A: ¬ (∃ i. t < max (te p i) (te q i))
  show False
  proof−
    have F1: ∀ i. te p i ≤ t
    proof
      fix i :: nat
      from A have ¬ (t < max (te p i) (te q i))
        by simp
      hence Eq1: max (te p i) (te q i) ≤ t by arith
      have Eq2: te p i ≤ max (te p i) (te q i)
        by (simp add: max-def)
      from Eq1 Eq2 show te p i ≤ t by simp
    qed

    have F2: ∀ (i :: nat). correct p (te p i)
    proof
      fix i :: nat
      from F1 have te p i ≤ t by simp
      from this corr-p correct-closed
      show correct p (te p i) by blast
    qed

    have F3: ∀ (i :: nat). real i ∗ rmin ≤ te p i
    proof
      fix i :: nat
      show real i ∗ rmin ≤ te p i
      proof (induct i)
        from synch0 show real (0::nat) ∗ rmin ≤ te p 0 by simp
      next
        fix i :: nat assume ind-hyp: real i ∗ rmin ≤ te p i

        show real (Suc i) ∗ rmin ≤ te p (Suc i)
```

```
      proof−

        have Eq1: real i ∗ rmin + rmin = (real i + 1)∗rmin
          by (simp add: distrib-right)
        have Eq2: real i + 1 = real (i+1) by simp
        from Eq1 Eq2
        have Eq3: real i ∗ rmin + rmin = real (i+1) ∗ rmin
          by presburger

        from F2 have cp1: correct p (te p (i+1))
          by simp
        from F2 have cp2: correct p (te p i)
          by simp
        from cp1 rts1d have rmin ≤ te p (i+1) − te p i
          by simp
        hence Eq4: te p i + rmin ≤ te p (i+1) by simp
        from ind-hyp have real i ∗ rmin + rmin ≤ te p i + rmin
          by (simp)
        from this Eq4 have real i ∗ rmin + rmin ≤ te p (i+1)
          by simp
        from this Eq3 show ?thesis by simp
      qed
    qed
  qed

  have F4: ∀ (i::nat). real i ∗ rmin ≤ t
  proof
    fix i::nat
    from F1 have te p i ≤ t by simp
    moreover
    from F3 have real i ∗ rmin ≤ te p i by simp
    ultimately show real i ∗ rmin ≤ t by simp
  qed

  from constants-ax have 0 < rmin by simp

  from this reals-Archimedean3
  have Archi: ∃ (k::nat). t < real k ∗ rmin
    by blast

  from Archi obtain k::nat where C: t < real k ∗ rmin ..

  from F4 have real k ∗ rmin ≤ t by simp
  hence notC: ¬ (t < real k ∗ rmin) by simp

  from C notC show False by simp
 qed
qed
```

2.3 Agreement property

```
definition γ1 x = π (2∗ϱ∗β + 2∗Λ) (2∗Λ + x + 2∗ϱ∗(rmax + β))
definition γ2 x = x + 2∗ϱ∗rmax
```

definition $\gamma 3\ x = \alpha\ (2{*}\Lambda + x + 2{*}\varrho{*}(rmax + \beta)) + \Lambda + 2{*}\varrho{*}\beta$

definition
$okmaxsync :: [nat, Clocktime] \Rightarrow bool$ **where**
$okmaxsync\ i\ x \longleftrightarrow (\forall\ p\ q.\ correct\ p\ (max\ (te\ p\ i)\ (te\ q\ i))$
$\wedge\ correct\ q\ (max\ (te\ p\ i)\ (te\ q\ i)) \longrightarrow$
$|IC\ p\ i\ (max\ (te\ p\ i)\ (te\ q\ i)) - IC\ q\ i\ (max\ (te\ p\ i)\ (te\ q\ i))| \leq x)$

definition
$okClocks :: [process, process, nat] \Rightarrow bool$ **where**
$okClocks\ p\ q\ i \longleftrightarrow (\forall\ t.\ 0 \leq t \wedge t < max\ (te\ p\ i)\ (te\ q\ i)$
$\wedge\ correct\ p\ t \wedge correct\ q\ t$
$\longrightarrow |VC\ p\ t - VC\ q\ t| \leq \delta)$

lemma *okClocks-sym*:
assumes *ok-pq*: $okClocks\ p\ q\ i$
shows $okClocks\ q\ p\ i$
proof−
{
fix $t :: time$
assume *ie1*: $0 \leq t$
assume *ie2*: $t < max\ (te\ q\ i)\ (te\ p\ i)$
assume *corr-q*: $correct\ q\ t$
assume *corr-p*: $correct\ p\ t$

have $max\ (te\ q\ i)\ (te\ p\ i) = max\ (te\ p\ i)\ (te\ q\ i)$
by (*simp add*: *max-def*)
from *this ok-pq ie1 ie2 corr-p corr-q*
have $|VC\ q\ t - VC\ p\ t| \leq \delta$
by(*simp add*: *abs-minus-commute okClocks-def*)
}
thus *?thesis* **by** (*simp add*: *okClocks-def*)
qed

lemma *ICp-Suc*:
assumes *corr-p*: $correct\ p\ (te\ p\ (i{+}1))$
shows $IC\ p\ (i{+}1)\ (te\ p\ (i{+}1)) = cfn\ p\ (\vartheta\ p\ (i{+}1))$
using *corr-p IClock* **by**(*simp add*: *Adj-def*)

lemma *IC-trans-inv*:
assumes *ie1*: $te\ q\ (i{+}1) \leq te\ p\ (i{+}1)$
and *corr-p*: $correct\ p\ (te\ p\ (i{+}1))$
and *corr-q*: $correct\ q\ (te\ p\ (i{+}1))$
shows
$IC\ q\ (i{+}1)\ (te\ p\ (i{+}1)) =$
$cfn\ q\ (\lambda\ n.\ \vartheta\ q\ (i{+}1)\ n + (PC\ q\ (te\ p\ (i{+}1)) - PC\ q\ (te\ q\ (i{+}1))))$
(**is** $?T1 = ?T2$)
proof−
let $?X = PC\ q\ (te\ p\ (i{+}1)) - PC\ q\ (te\ q\ (i{+}1))$

from *corr-q ie1 PC-monotone* **have** *posX*: $0 \leq ?X$
by (*simp add*: *le-diff-eq*)

```
  from IClock corr-q have ?T1 = cfn q (ϑ q (i+1)) + ?X
    by(simp add: Adj-def)

  from this posX trans-inv show ?thesis by simp
qed

lemma beta-rho:
assumes ie: te q (i+1) ≤ te p (i+1)
and corr-p: correct p (te p (i+1))
and corr-q: correct q (te p (i+1))
and corr-l: correct l (te p (i+1))
shows |(PC l (te p (i+1)) − PC l (te q (i+1))) − (te p (i+1) − te q (i+1))| ≤ β∗ϱ
proof−
  let ?X = (PC l (te p (i+1)) − PC l (te q (i+1)))
  let ?D = te p (i+1) − te q (i+1)

  from ie have posD: 0 ≤ ?D by simp

  from ie PC-monotone corr-l have posX: 0 ≤ ?X
    by (simp add: le-diff-eq)
  from ie corr-l rate-1 have bound1: ?X ≤ ?D ∗ (1 + ϱ) by simp
  from ie corr-l correct-closed have corr-l-tq: correct l (te q (i+1))
    by(blast)
  from ie corr-q correct-closed have corr-q-tq: correct q (te q (i+1))
    by blast
  from corr-q-tq corr-p rts2b have |?D| ≤ β
    by(simp)
  from this constants-ax posD have D-beta: ?D∗ϱ ≤ β∗ϱ
    by(simp add: abs-if)

  show ?thesis
  proof cases
    assume A: ?D ≤ ?X
    from posX posD A have absEq: |?X − ?D| = ?X − ?D
      by(simp add: abs-if)
    from bound1 have bound2: ?X − ?D ≤ ?D∗ϱ
      by(simp add: mult.commute distrib-right)
    from D-beta absEq bound2 show ?thesis by simp
  next
    assume notA: ¬ (?D ≤ ?X)
    from this have absEq2: |?X − ?D| = ?D − ?X
      by(simp add: abs-if)
    from ie corr-l rate-2 have bound3: ?D∗(1 − ϱ) ≤ ?X by simp
    from this have ?D − ?X ≤ ?D∗ϱ by (simp add: algebra-simps)
    from this absEq2 D-beta show ?thesis by simp
  qed
qed
```

This lemma (and the next one pe-cond2) proves an assumption used in the precision enhancement.

```
lemma pe-cond1:
assumes ie: te q (i+1) ≤ te p (i+1)
and corr-p: correct p (te p (i+1))
and corr-q: correct q (te p (i + 1))
```

```
and corr-l: correct l (te p (i+1))
shows |ϑ q (i+1) l + (PC q (te p (i+1)) − PC q (te q (i+1))) −
        ϑ p (i+1) l| ≤ 2∗ ϱ ∗ β + 2∗Λ
(is ?M ≤ ?N)
proof−
  let ?Xl = (PC l (te p (i+1)) − PC l (te q (i+1)))
  let ?Xq = (PC q (te p (i+1)) − PC q (te q (i+1)))
  let ?D = te p (i+1) − te q (i+1)
  let ?T = ϑ p (i+1) l − ϑ q (i+1) l
  let ?RE1 = ϑ p (i+1) l − IC l i (te p (i+1))
  let ?RE2 = ϑ q (i+1) l − IC l i (te q (i+1))
  let ?ICT = IC l i (te p (i+1)) − IC l i (te q (i+1))

  have ?M = |(?Xq − ?D) − (?T − ?D)|
  by(simp add: abs-if)

  hence Split: ?M ≤ |?Xq − ?D| + |?T − ?D|
    by(simp add: abs-if)

  from ie corr-q correct-closed have corr-q-tq: correct q (te q (i+1))
    by(blast)
  from ie corr-l correct-closed have corr-l-tq: correct l (te q (i+1))
    by blast

  from corr-p corr-q corr-l ie beta-rho
  have XlD: |?Xl − ?D| ≤ β∗ϱ
    by simp

  from corr-p corr-q ie beta-rho
  have XqD: |?Xq − ?D| ≤ β∗ϱ by simp

  have TD: |?T − ?D| ≤ 2∗Λ + β∗ϱ
  proof−
    have Eq1: |?T − ?D| = |(?T − ?ICT) + (?ICT − ?D)| (is ?E1 = ?E2)
      by (simp add: abs-if)

    have Eq2: ?E2 ≤ |?T − ?ICT| + |?ICT − ?D|
      by(simp add: abs-if)

    have Eq3: |?T − ?ICT| ≤  |?RE1| + |?RE2|
      by(simp add: abs-if)

    from readerror corr-p corr-l
    have Eq4: |?RE1| ≤ Λ by simp


    from corr-l-tq corr-q-tq this readerror
    have Eq5: |?RE2| ≤ Λ by simp

    from Eq3 Eq4 Eq5 have Eq6: |?T − ?ICT| ≤ 2∗Λ
      by simp

    have Eq7: ?ICT − ?D = ?Xl − ?D
```

```
    proof−
      from corr-p rte have te p i ≤ te p (i+1)
        by(simp)
      from this corr-l correct-closed have corr-l-tpi: correct l (te p i)
        by blast
      from corr-q-tq rte have te q i ≤ te q (i+1)
        by simp
      from this corr-l-tq correct-closed have corr-l-tqi: correct l (te q i)
        by blast

      from IClock corr-l
      have F1: IC l i (te p (i+1)) = PC l (te p (i+1)) + Adj l i
        by(simp)
      from IClock corr-l-tq
      have F2: IC l i (te q (i+1)) = PC l (te q (i+1)) + Adj l i
        by simp
      from F1 F2 show ?thesis by(simp)
    qed

    from this XlD have Eq8: |?ICT − ?D| ≤ β∗ϱ
      by arith
    from Eq1 Eq2 Eq6 Eq8 show ?thesis
      by(simp)
  qed

  from Split XqD TD have F1: ?M ≤ 2∗ β ∗ ϱ + 2∗Λ
    by(simp)
  have F2: 2 ∗ ϱ ∗ β + 2∗Λ = 2∗ β ∗ ϱ + 2∗Λ
    by simp
  from F1 show ?thesis by (simp only: F2)

qed

lemma pe-cond2:
assumes ie: te m i ≤ te l i
and corr-k: correct k (te k (i+1))
and corr-l-tk: correct l (te k (i+1))
and corr-m-tk: correct m (te k (i+1))
and ind-hyp: |IC l i (te l i) − IC m i (te l i)| ≤ δS
shows |ϑ k (i+1) l − ϑ k (i+1) m| ≤ 2∗Λ + δS + 2∗ϱ∗(rmax + β)
proof−
  let ?X = ϑ k (i+1) l − ϑ k (i+1) m
  let ?N = 2∗Λ + δS + 2∗ϱ∗(rmax + β)
  let ?D1 = ϑ k (i+1) l − IC l i (te k (i+1))
  let ?D2 = ϑ k (i+1) m − IC m i (te k (i+1))
  let ?ICS = IC l i (te k (i+1)) − IC m i (te k (i+1))
  let ?tlm = te l i
  let ?IC = IC l i ?tlm − IC m i ?tlm

  have Eq1: |?X| = |(?D1 − ?D2) + ?ICS| (is ?E1 = ?E2)
    by (simp add: abs-if)

  have Eq2: ?E2 ≤ |?D1 − ?D2| + |?ICS| by (simp add: abs-if)
```

```
  from corr-l-tk corr-k beta-bound1 have ie-lk: te l i ≤ te k (i+1)
    by (simp add: le-diff-eq)

  from this corr-l-tk correct-closed have corr-l: correct l (te l i)
    by blast

  from ie-lk corr-l-tk corr-m-tk IC-bd
  have Eq3: |?ICS| ≤ |?IC| + 2∗ϱ∗(te k (i+1) − ?tlm)
    by simp
  from this ind-hyp have Eq4: |?ICS| ≤ δS + 2∗ϱ∗(te k (i+1) − ?tlm)
    by simp

  from corr-l corr-k beta-bound2 have te k (i+1) − ?tlm ≤ rmax + β
    by simp
  from this constants-ax have 2∗ϱ∗(te k (i+1) − ?tlm) ≤ 2∗ϱ∗(rmax + β)
    by simp
  from this Eq4 have Eq4a: |?ICS| ≤ δS + 2∗ϱ∗(rmax + β)
    by simp

  from corr-k corr-l-tk readerror
  have Eq5: |?D1| ≤ Λ by simp
  from corr-k corr-m-tk readerror
  have Eq6: |?D2| ≤ Λ by simp
  have |?D1 − ?D2| ≤ |?D1| + |?D2| by (simp add: abs-if)
  from this Eq5 Eq6 have Eq7: |?D1 − ?D2| ≤ 2∗Λ
    by (simp)

  from Eq1 Eq2 Eq4a Eq7 split show ?thesis by (simp)
qed

lemma theta-bound:
assumes corr-l: correct l (te p (i+1))
and corr-m: correct m (te p (i+1))
and corr-p: correct p (te p (i+1))
and IC-bound:
    |IC l i (max (te l i) (te m i)) − IC m i (max (te l i) (te m i))|
      ≤ δS
shows |ϑ p (i+1) l − ϑ p (i+1) m|
      ≤  2∗Λ + δS + 2∗ϱ∗(rmax + β)
proof−
  from corr-p corr-l beta-bound1 have tli-le-tp: te l i ≤ te p (i+1)
    by (simp add: le-diff-eq)
  from corr-p corr-m beta-bound1 have tmi-le-tp: te m i ≤ te p (i+1)
    by (simp add: le-diff-eq)

  let ?tml = max (te l i) (te m i)
  from tli-le-tp tmi-le-tp have tml-le-tp: ?tml ≤ te p (i+1)
    by simp

  from tml-le-tp corr-l correct-closed have corr-l-tml: correct l ?tml
    by blast
  from tml-le-tp corr-m correct-closed have corr-m-tml: correct m ?tml
```

```
    by blast

  let ?Y = 2*Λ + δS + 2*ϱ*(rmax + β)
  show |ϑ p (i+1) l − ϑ p (i+1) m| ≤ ?Y
  proof cases
    assume A: te m i < te l i

    from this IC-bound
    have |IC l i (te l i) − IC m i (te l i)| ≤ δS
      by(simp add: max-def)
    from this A corr-p corr-l corr-m pe-cond2
    show ?thesis by(simp)
  next
    assume ¬ (te m i < te l i)
    hence Eq1: te l i ≤ te m i by simp
    from this IC-bound
    have Eq2: |IC l i (te m i) − IC m i (te m i)| ≤ δS
      by(simp add: max-def)

    hence |IC m i (te m i) − IC l i (te m i)| ≤ δS
      by (simp add: abs-minus-commute)
    from this Eq1 corr-p corr-l corr-m pe-cond2
    have |ϑ p (i+1) m − ϑ p (i+1) l| ≤ ?Y
      by(simp)
    thus ?thesis by (simp add: abs-minus-commute)
  qed
qed

lemma four-one-ind-half:
  assumes ie1: β ≤ rmin
  and ie2: μ ≤ δS
  and ie3: γ1 δS ≤ δS
  and ind-hyp: okmaxsync i δS
  and ie4: te q (i+1) ≤ te p (i+1)
  and corr-p: correct p (te p (i+1))
  and corr-q: correct q (te p (i+1))
shows |IC p (i+1) (te p (i+1)) − IC q (i+1) (te p (i+1))| ≤ δS
proof−
  let ?tpq = te p (i+1)

  let ?f = λ n. ϑ q (i+1) n + (PC q (te p (i+1)) − PC q (te q (i+1)))
  let ?g = ϑ p (i+1)

  from ie4 corr-q correct-closed have corr-q-tq: correct q (te q (i+1))
    by blast

  have Eq-IC-cfn: |IC p (i+1) ?tpq − IC q (i+1) ?tpq| =
    |cfn q ?f − cfn p ?g|
  proof−
    from corr-p ICp-Suc have Eq1: IC p (i+1) ?tpq = cfn p ?g by simp

    from ie4 corr-p corr-q IC-trans-inv
    have Eq2: IC q (i+1) ?tpq = cfn q ?f by simp
```

```
  from Eq1 Eq2 show ?thesis by(simp add: abs-if)
qed

let ?ppred = λ l. correct l (te p (i+1))

let ?X = 2*ϱ*β + 2*Λ
have ∀ l. ?ppred l ⟶ |?f l − ?g l| ≤ ?X
proof −
  {
    fix l
    assume ?ppred l
    from ie4 corr-p corr-q this pe-cond1
    have |?f l − ?g l| ≤ (2*ϱ*β + 2*Λ)
      by(auto)
  }
  thus ?thesis by blast
qed
hence cond1: okRead2 ?f ?g ?X ?ppred
  by(simp add: okRead2-def)

let ?Y = 2*Λ + δS + 2*ϱ*(rmax + β)

have ∀ l m. ?ppred l ∧ ?ppred m ⟶ |?f l − ?f m| ≤ ?Y
proof−
  {
    fix l m
    assume corr-l: ?ppred l
    assume corr-m: ?ppred m

    from corr-p corr-l beta-bound1 have tli-le-tp: te l i ≤ te p (i+1)
      by (simp add: le-diff-eq)
    from corr-p corr-m beta-bound1 have tmi-le-tp: te m i ≤ te p (i+1)
      by (simp add: le-diff-eq)

    let ?tlm = max (te l i) (te m i)

    from tli-le-tp tmi-le-tp have tlm-le-tp: ?tlm ≤ te p (i+1)
      by simp

    from ie4 corr-l correct-closed have corr-l-tq: correct l (te q (i+1))
      by blast
    from ie4 corr-m correct-closed have corr-m-tq: correct m (te q (i+1))
      by blast
    from tlm-le-tp corr-l correct-closed have corr-l-tlm: correct l ?tlm
      by blast
    from tlm-le-tp corr-m correct-closed have corr-m-tlm: correct m ?tlm
      by blast

    from ind-hyp corr-l-tlm corr-m-tlm
    have EqAbs1: |IC l i ?tlm − IC m i ?tlm| ≤ δS
      by(auto simp add: okmaxsync-def)
```

```
    have EqAbs3: |?f l − ?f m| = |ϑ q (i+1) l − ϑ q (i+1) m|
      by (simp add: abs-if)

    from EqAbs1 corr-q-tq corr-l-tq corr-m-tq theta-bound
    have |ϑ q (i+1) l − ϑ q (i+1) m| ≤ ?Y
      by simp
    from this EqAbs3  have |?f l − ?f m| ≤ ?Y
      by simp
  }
  thus ?thesis by simp
qed
hence cond2a: okRead1 ?f ?Y ?ppred by (simp add: okRead1-def)

have ∀ l m. ?ppred l ∧ ?ppred m ⟶ |?g l − ?g m| ≤ ?Y
proof−
  {
    fix l m
    assume corr-l: ?ppred l
    assume corr-m: ?ppred m

    from corr-p corr-l beta-bound1 have tli-le-tp: te l i ≤ te p (i+1)
      by (simp add: le-diff-eq)
    from corr-p corr-m beta-bound1 have tmi-le-tp: te m i ≤ te p (i+1)
      by (simp add: le-diff-eq)

    let ?tlm = max (te l i) (te m i)
    from tli-le-tp tmi-le-tp have tlm-le-tp: ?tlm ≤ te p (i+1)
      by simp

    from tlm-le-tp corr-l correct-closed have corr-l-tlm: correct l ?tlm
      by blast
    from tlm-le-tp corr-m correct-closed have corr-m-tlm: correct m ?tlm
      by blast

    from ind-hyp corr-l-tlm corr-m-tlm
    have EqAbs1: |IC l i ?tlm − IC m i ?tlm| ≤ δS
      by(auto simp add: okmaxsync-def)

    from EqAbs1 corr-p corr-l corr-m theta-bound
    have |?g l − ?g m| ≤ ?Y by simp
  }
  thus ?thesis by simp
qed
hence cond2b: okRead1 ?g ?Y ?ppred by (simp add: okRead1-def)

from correct-count have np − maxfaults ≤ count ?ppred np
  by simp
from this corr-p corr-q cond1 cond2a cond2b prec-enh
have |cfn q ?f − cfn p ?g| ≤ π ?X ?Y
  by blast

from ie3 this have |cfn q ?f − cfn p ?g| ≤ δS
  by (simp add: γ1-def)
```

```
  from this Eq-IC-cfn show ?thesis by (simp)
qed
```

Theorem 4.1 in Shankar's paper.

```
theorem four-one:
  assumes ie1: β ≤ rmin
  and ie2: μ ≤ δS
  and ie3: γ1 δS ≤ δS
shows okmaxsync i δS
proof(induct i)
  show okmaxsync 0 δS
  proof−
    {
      fix p q
      assume corr-p: correct p (max (te p 0) (te q 0))
      assume corr-q: correct q (max (te p 0) (te q 0))

      from corr-p synch0 have cp0: correct p 0 by simp
      from corr-q synch0 have cq0: correct q 0 by simp

      from synch0 cp0 cq0 IClock
      have IC-eq-PC:
        |IC p 0 (max (te p 0) (te q 0)) − IC q 0 (max (te p 0) (te q 0))|
         = |PC p 0 − PC q 0| (is ?T1 = ?T2)
        by(simp add: Adj-def)

      from ie2 init synch0 cp0 have range1: 0 ≤ PC p 0 ∧ PC p 0 ≤ δS
        by auto
      from ie2 init synch0 cq0 have range2: 0 ≤ PC q 0 ∧ PC q 0 ≤ δS
        by auto
      have ?T2 ≤ δS
      proof cases
        assume A:PC p 0 < PC q 0
        from A range1 range2 show ?thesis
          by(auto simp add: abs-if)
      next
        assume notA: ¬ (PC p 0 < PC q 0)
        from notA range1 range2 show ?thesis
          by(auto simp add: abs-if)
      qed
      from this IC-eq-PC have ?T1 ≤ δS by simp
    }
    thus ?thesis by (simp add: okmaxsync-def)
  qed
next
  fix i assume ind-hyp: okmaxsync i δS
  show okmaxsync (Suc i) δS
  proof−
    {
      fix p q
      assume corr-p: correct p (max (te p (i + 1)) (te q (i + 1)))
      assume corr-q: correct q (max (te p (i + 1)) (te q (i + 1)))
```

```
      let ?tp = te p (i + 1)
      let ?tq = te q (i + 1)
      let ?tpq = max ?tp ?tq

      have |IC p (i+1) ?tpq − IC q (i+1) ?tpq| ≤ δS (is ?E1 ≤ δS)
      proof cases
        assume A: ?tq < ?tp
        from A corr-p have cp1: correct p (te p (i+1))
          by (simp add: max-def)
        from A corr-q have cq1: correct q (te p (i+1))
          by (simp add: max-def)
        from A
        have Eq1: ?E1 = |IC p (i+1) (te p (i+1)) − IC q (i+1) (te p (i+1))|
                (is ?E1 = ?E2)
          by (simp add: max-def)
        from A cp1 cq1 corr-p corr-q ind-hyp ie1 ie2 ie3
          four-one-ind-half
        have ?E2 ≤ δS by (simp)
        from this Eq1 show ?thesis by simp
      next
        assume notA: ¬ (?tq < ?tp)
        from this corr-p have cp2: correct p (te q (i+1))
          by (simp add: max-def)
        from notA corr-q have cq2: correct q (te q (i+1))
          by (simp add: max-def)
        from notA
        have Eq2: ?E1 = |IC q (i+1) (te q (i+1)) − IC p (i+1) (te q (i+1))|
                (is ?E1 = ?E3)
          by (simp add: max-def abs-minus-commute)
        from notA have ?tp ≤ ?tq by simp
        from this cp2 cq2 ind-hyp ie1 ie2 ie3 four-one-ind-half
        have ?E3 ≤ δS
          by simp
        from this Eq2 show ?thesis by (simp)
      qed
    }
    thus ?thesis by (simp add: okmaxsync-def)
  qed
qed

lemma VC-cfn:
  assumes corr-p: correct p (te p (i+1))
  and ie: te p (i+1) < te p (i+2)
shows VC p (te p (i+1)) = cfn p (ϑ p (i+1))
proof−
  from ie corr-p VClock have VC p (te p (i+1)) = IC p (i+1) (te p (i+1))
    by simp
  moreover
  from corr-p IClock
  have IC p (i+1) (te p (i+1)) = PC p (te p (i+1)) + Adj p (i+1)
    by blast
  moreover
  have PC p (te p (i+1)) + Adj p (i+1) = cfn p (ϑ p (i+1))
```

```
    by(simp add: Adj-def)
  ultimately show ?thesis by simp
qed
```

Lemma for the inductive case in Theorem 4.2

```
lemma four-two-ind:
  assumes ie1: β ≤ rmin
  and ie2: μ ≤ δS
  and ie3: γ1 δS ≤ δS
  and ie4: γ2 δS ≤ δ
  and ie5: γ3 δS ≤ δ
  and ie6: te q (i+1) ≤ te p (i+1)
  and ind-hyp: okClocks p q i
  and t-bound1: 0 ≤ t
  and t-bound2: t < max (te p (i+1)) (te q (i+1))
  and t-bound3: max (te p i) (te q i) ≤ t
  and tpq-bound: max (te p i) (te q i) < max (te p (i+1)) (te q (i+1))
  and corr-p: correct p t
  and corr-q: correct q t
shows |VC p t − VC q t| ≤ δ
proof cases
  assume A: t < te q (i+1)

  let ?tpq = max (te p i) (te q i)

  have Eq1: te p i ≤ t ∧ te q i ≤ t
  proof cases
    assume te p i ≤ te q i
    from this  t-bound3 show ?thesis by (simp add: max-def)
  next
    assume ¬ (te p i ≤ te q i)
    from this t-bound3 show ?thesis by (simp add: max-def)
  qed

  from ie6 have tp-max: max (te p (i+1)) (te q (i+1)) = te p (i+1)
    by(simp add: max-def)
  from this t-bound2 have Eq2: t < te p (i+1) by simp

  from VClock Eq1 Eq2 corr-p have Eq3: VC p t = IC p i t by simp

  from VClock Eq1 A corr-q have Eq4: VC q t = IC q i t by simp
  from Eq3 Eq4 have Eq5: |VC p t − VC q t| = |IC p i t − IC q i t|
    by simp

  from t-bound3 corr-p corr-q correct-closed
  have corr-tpq: correct p ?tpq ∧ correct q ?tpq
    by(blast)

  from t-bound3 IC-bd corr-p corr-q
  have Eq6: |IC p i t − IC q i t|  ≤ |IC p i ?tpq − IC q i ?tpq|
    + 2∗ϱ∗(t − ?tpq) (is ?E1 ≤ ?E2)
    by(blast)
```

```
  from ie1 ie2 ie3 four-one have okmaxsync i δS by simp

  from this corr-tpq have |IC p i ?tpq − IC q i ?tpq| ≤ δS
    by(simp add: okmaxsync-def)

  from Eq6 this  have Eq7: ?E1 ≤ δS + 2∗ϱ∗(t − ?tpq) by simp

  from corr-p Eq2 rts0 have t − te p i ≤ rmax by simp
  from this have t − ?tpq ≤ rmax by (simp add: max-def)
  from this constants-ax have 2∗ϱ∗(t − ?tpq) ≤ 2∗ϱ∗rmax
    by simp
  hence δS + 2∗ϱ∗(t − ?tpq) ≤ δS + 2∗ϱ∗rmax
    by simp
  from this Eq7 have ?E1 ≤ δS + 2∗ϱ∗rmax by simp
  from this Eq5 ie4 show ?thesis by(simp add: γ2-def)
next
  assume ¬ (t < te q (i+1))
  hence  B: te q (i+1) ≤ t by simp

  from ie6 t-bound2
  have tp-max: max (te p (i+1)) (te q (i+1)) = te p (i+1)
    by(simp add: max-def)

  have te p i ≤ max (te p i) (te q i)
    by(simp add: max-def)

  from this t-bound3 have tp-bound1: te p i ≤ t by simp

  from tp-max t-bound2 have tp-bound2: t < te p (i+1) by simp

  have tq-bound1: t < te q (i+2)
  proof (rule ccontr)
    assume ¬ (t < te q (i+2))
    hence C: te q (i+2) ≤ t by simp

    from C corr-q correct-closed
    have corr-q-t2: correct q (te q (i+2)) by blast

    have te q (i+1) + β ≤ t
    proof−
      from corr-q-t2 rts1d have rmin ≤ te q (i+2) − te q (i+1)
        by simp
      from this ie1 have β ≤ te q (i+2) − te q (i+1)
        by simp
      hence te q (i+1) + β ≤ te q (i+2) by simp
      from this C show ?thesis by simp
    qed
    from this corr-p corr-q rts2a have te p (i+1) ≤ t
      by blast
    hence ¬ (t < te p (i+1)) by simp
    from this tp-bound2 show False by simp
  qed
```

from *tq-bound1 B* **have** *tq-bound2*: *te q* (*i*+*1*) < *te q* (*i*+*2*) **by** *simp*
from *B tp-bound2* **have** *tq-bound3*: *te q* (*i*+*1*) < *te p* (*i*+*1*)
  by *simp*
from *B corr-p correct-closed*
have *corr-p-tq1*: *correct p* (*te q* (*i*+*1*)) **by** *blast*

from *B correct-closed corr-q*
have *corr-q-tq1*: *correct q* (*te q* (*i*+*1*)) **by** *blast*

from *corr-p-tq1 corr-q-tq1 beta-bound1*
have *tq-bound4*: *te p i* ≤ *te q* (*i*+*1*)
  by(*simp add*: *le-diff-eq*)

from *tq-bound1 VClock B corr-q*
have *Eq1*: *VC q t* = *IC q* (*i*+*1*) *t* **by** *simp*

from *VClock tp-bound1 tp-bound2 corr-p*
have *Eq2*: *VC p t* = *IC p i t* **by** *simp*

from *Eq1 Eq2* **have** *Eq3*: |*VC p t* − *VC q t*| = |*IC p i t* − *IC q* (*i*+*1*) *t*|
  by *simp*

from *B corr-p corr-q IC-bd*
have |*IC p i t* − *IC q* (*i*+*1*) *t*| ≤
  |*IC p i* (*te q* (*i*+*1*)) − *IC q* (*i*+*1*) (*te q* (*i*+*1*))| + *2*∗*ϱ*∗(*t* − *te q* (*i*+*1*))
  by *simp*

from *this Eq3*
have *VC-split*: |*VC p t* − *VC q t*| ≤
  |*IC p i* (*te q* (*i*+*1*)) − *IC q* (*i*+*1*) (*te q* (*i*+*1*))| + *2*∗*ϱ*∗(*t* − *te q* (*i*+*1*))
  by *simp*

from *tq-bound2 VClock corr-q-tq1*
have *Eq4*: *VC q* (*te q* (*i*+*1*)) = *IC q* (*i*+*1*) (*te q* (*i*+*1*)) **by** *simp*

from *this tq-bound2 VC-cfn corr-q-tq1*
have *Eq5*: *IC q* (*i*+*1*) (*te q* (*i*+*1*)) = *cfn q* (*ϑ q* (*i*+*1*)) **by** *simp*

hence *IC-eq-cfn*: *IC p i* (*te q* (*i*+*1*)) − *IC q* (*i*+*1*) (*te q* (*i*+*1*)) =
  IC p i (*te q* (*i*+*1*)) − *cfn q* (*ϑ q* (*i*+*1*))
  (**is** *?E1* = *?E2*)
  by *simp*

let *?f* = *ϑ q* (*i*+*1*)
let *?ppred* = λ *l*. *correct l* (*te q* (*i*+*1*))
let *?X* = *2*∗Λ + *δS* + *2*∗*ϱ*∗(*rmax* + *β*)

have ∀ *l m*. *?ppred l* ∧ *?ppred m* ⟶ |*ϑ q* (*i*+*1*) *l* − *ϑ q* (*i*+*1*) *m*| ≤ *?X*
proof−
  {
    fix *l* :: *process*
    fix *m* :: *process*
    assume *corr-l*: *?ppred l*

```
    assume corr-m: ?ppred m

    let ?tlm = max (te l i) (te m i)
    have tlm-bound: ?tlm ≤ te q (i+1)
    proof−
      from corr-l corr-q-tq1 beta-bound1 have te l i ≤ te q (i+1)
        by (simp add: le-diff-eq)
      moreover
      from corr-m corr-q-tq1 beta-bound1 have te m i ≤ te q (i+1)
        by (simp add: le-diff-eq)
      ultimately show ?thesis by simp
    qed

    from tlm-bound corr-l corr-m correct-closed
    have corr-tlm: correct l ?tlm ∧ correct m ?tlm
      by blast

    have |IC l i ?tlm − IC m i ?tlm| ≤ δS
    proof−
      from ie1 ie2 ie3 four-one  have okmaxsync i δS
        by simp
      from this corr-tlm show ?thesis by(simp add: okmaxsync-def)
    qed

    from this corr-l corr-m corr-q-tq1 theta-bound
    have |ϑ q (i+1) l − ϑ q (i+1) m| ≤ ?X by simp
  }
  thus ?thesis by blast
qed
hence readOK: okRead1 (ϑ q (i+1)) ?X ?ppred
  by(simp add: okRead1-def)

let ?E3 = cfn q (ϑ q (i+1)) − ϑ q (i+1) p
let ?E4 = ϑ q (i+1) p − IC p i (te q (i+1))

have |?E2| = |?E3 + ?E4| by (simp add: abs-if)
hence Eq8: |?E2| ≤ |?E3| + |?E4| by (simp add: abs-if)

from correct-count have ppredOK: np − maxfaults ≤ count ?ppred np
  by simp
from readOK ppredOK corr-p-tq1 corr-q-tq1 acc-prsv
have |?E3| ≤ α ?X
  by blast
from this Eq8 have Eq9: |?E2| ≤ α ?X + |?E4| by simp

from corr-p-tq1 corr-q-tq1 readerror
have |?E4| ≤ Λ by simp

from this Eq9 have Eq10: |?E2| ≤ α ?X + Λ by simp

from this VC-split IC-eq-cfn
have almost-right:
  |VC p t − VC q t| ≤
```

```
    α ?X + Λ + 2∗ϱ∗(t − te q (i+1))
    by simp

  have t − te q (i+1) ≤ β
  proof (rule ccontr)
    assume ¬ (t − te q (i+1) ≤ β)
    hence te q (i+1) + β ≤ t by simp
    from this corr-p corr-q rts2a have te p (i+1) ≤ t
      by auto
    hence ¬ (t < te p (i+1)) by simp
    from this tp-bound2 show False
      by simp
  qed

  from this constants-ax
  have α ?X + Λ + 2∗ϱ∗(t − te q (i+1))
        ≤ α ?X + Λ + 2∗ϱ∗β
    by (simp)

  from this almost-right
  have |VC p t − VC q t| ≤ α ?X + Λ + 2∗ϱ∗β
    by arith

  from this ie5 show ?thesis by (simp add: γ3-def)
qed
```

Theorem 4.2 in Shankar's paper.

```
theorem four-two:
  assumes ie1: β ≤ rmin
  and ie2: μ ≤ δS
  and ie3: γ1 δS ≤ δS
  and ie4: γ2 δS ≤ δ
  and ie5: γ3 δS ≤ δ
shows okClocks p q i
proof (induct i)
  show okClocks p q 0
  proof−
    {
      fix t :: time
      assume t-bound1: 0 ≤ t
      assume t-bound2: t < max (te p 0) (te q 0)
      assume corr-p: correct p t
      assume corr-q: correct q t
      from t-bound2 synch0 have t < 0
        by(simp add: max-def)
      from this t-bound1 have False by simp
      hence |VC p t − VC q t| ≤ δ by simp
    }
    thus ?thesis by (simp add: okClocks-def)
  qed
next
  fix i::nat assume ind-hyp: okClocks p q i
  show okClocks p q (Suc i)
```

```
proof −
  {
    fix t :: time
    assume t-bound1: 0 ≤ t
    assume t-bound2: t < max (te p (i+1)) (te q (i+1))
    assume corr-p: correct p t
    assume corr-q: correct q t

    let ?tpq1 = max (te p i) (te q i)
    let ?tpq2 = max (te p (i+1)) (te q (i+1))

    have |VC p t − VC q t| ≤ δ
    proof cases
      assume tpq-bound: ?tpq1 < ?tpq2
      show ?thesis
      proof cases
        assume t < ?tpq1
        from t-bound1 this  corr-p corr-q ind-hyp
        show ?thesis by(simp add: okClocks-def)
      next
        assume ¬ (t < ?tpq1)
        hence tpq-le-t: ?tpq1 ≤ t by arith

        show ?thesis
        proof cases
          assume A: te q (i+1) ≤ te p (i+1)

          from this tpq-le-t tpq-bound ie1 ie2 ie3 ie4 ie5
            ind-hyp t-bound1 t-bound2
            corr-p corr-q tpq-bound four-two-ind
          show ?thesis by(simp)
        next
          assume ¬ (te q (i+1) ≤ te p (i+1))
          hence B: te p (i+1) ≤ te q (i+1) by simp

          from ind-hyp okClocks-sym have ind-hyp1: okClocks q p i
            by blast

          have maxsym1: max (te p (i+1)) (te q (i+1)) = max (te q (i+1)) (te p (i+1))
            by (simp add: max-def)
          have maxsym2: max (te p i) (te q i) = max (te q i) (te p i)
            by (simp add: max-def)

          from maxsym1 t-bound2
          have t-bound21: t < max (te q (i+1)) (te p (i+1))
            by simp

          from maxsym1 maxsym2 tpq-bound
          have tpq-bound1: max (te q i) (te p i) < max (te q (i+1)) (te p (i+1))
            by simp
          from maxsym2 tpq-le-t
          have tpq-le-t1: max (te q i) (te p i) ≤ t by simp
```

```
        from B tpq-le-t1 tpq-bound1 ie1 ie2 ie3 ie4 ie5
          ind-hyp1 t-bound1 t-bound21
          corr-p corr-q tpq-bound four-two-ind
        have |VC q t − VC p t| ≤ δ by(simp)
        thus ?thesis by (simp add: abs-minus-commute)
      qed

    qed
  next
    assume ¬ (?tpq1 < ?tpq2)
    hence ?tpq2 ≤ ?tpq1 by arith
    from t-bound2 this have t < ?tpq1 by arith
    from t-bound1 this corr-p corr-q ind-hyp
    show ?thesis by(simp add: okClocks-def)
  qed
 }
 thus ?thesis by (simp add: okClocks-def)
qed
qed
```

The main theorem: all correct clocks are synchronized within the bound delta.

```
theorem agreement:
  assumes ie1: β ≤ rmin
  and ie2: μ ≤ δS
  and ie3: γ1 δS ≤ δS
  and ie4: γ2 δS ≤ δ
  and ie5: γ3 δS ≤ δ
  and ie6: 0 ≤ t
  and cpq: correct p t ∧ correct q t
shows |VC p t − VC q t| ≤ δ
proof−
  from ie6 cpq event-bound have ∃ i :: nat. t < max (te p i) (te q i)
    by simp
  from this obtain i :: nat where t-bound: t < max (te p i) (te q i) ..

  from t-bound ie1 ie2 ie3 ie4 ie5 four-two have okClocks p q i
    by simp

  from ie6 this t-bound cpq show ?thesis
    by (simp add: okClocks-def)
qed

end
```

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