Uncertainty and Predictability: can they be reconciled?

A Vision and a Concrete Model

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The Vision

Problem Motivation

- Design and deployment of distributed applications is faced with the confluence of antagonistic aims:
  - between what is required by applications, and what is given by the supporting infrastructure/ environment
- Current and future large, massive-scale pervasive and/or ubiquitous computing systems will amplify this:
  - very high numbers of players, very large distances, geographical scope, topology and interconnections no longer a given, ill-defined COTS component properties
- Key lies with a changing notion of service guarantees:
  - about what have always been the fundamental issues, e.g., consistency, synchronism, reliability, availability, predictability, security, ...

Problem Motivation

- Take the time dimension
- Many services, beyond mere performance, have to secure *timeliness* properties, that is, they have to meet timing constraints (every x ms, within T, until T, etc.)
  - Dependability constraints: control applications; User-dictated QoS: Multimedia apps, synchronized groupware
- So we should use synchronous system models...:
  - But with unpredictable or unreliable infrastructures the system may fail
  - Dedicated infrastructures may be impractical or expensive
- Why not use asynchronous system models then?
  - They do not allow timeliness specifications

Grand challenges put by this scenario?

- Looks like a grand challenge would be withstanding uncertainty whilst achieving predictability
- Uncertainty:
  - ☞ is a common denominator of current systems
  - ☞ uncertain synchrony, fault model, and even topology
- Predictability:
  - ☞ systems are required to fulfil more and more demanding goals which imply predictability or determinism, e.g, timeliness, security
- Reconciling them means:
  - ☞ strong attributes (e.g. on ordering, agreement, timely termination of algorithms) can be secured in settings where usually very little is assumed and very little is expected from

Meeting the challenge

- Are there scientific advances we can look forward to?

a conflict must be solved between the weakness of the environment and the relative strength of requirements

- We propose to address this conflict with a "first-things-first" approach:

define adequate system model and architecture
before thinking about algorithms/protocols/mechanisms

Partial Solutions (in the time dimension)

- Models of intermediate synchrony have been around:
  - Partially synchronous (Dolev, Dwork)
  - Asynchronous with Failure Detectors (Chandra/Toueg)
  - Timed Asynchronous Model (Cristian/Fetzer)
  - Quasi-Synchronous Model (Veríssimo/Almeida)
- Did they solve the problem? Only partially ☺

A common feature we observed in these works: synchronism (or asynchronism) are not homogeneous properties of systems--- they vary with time and with space, i.e. the part of the system being considered

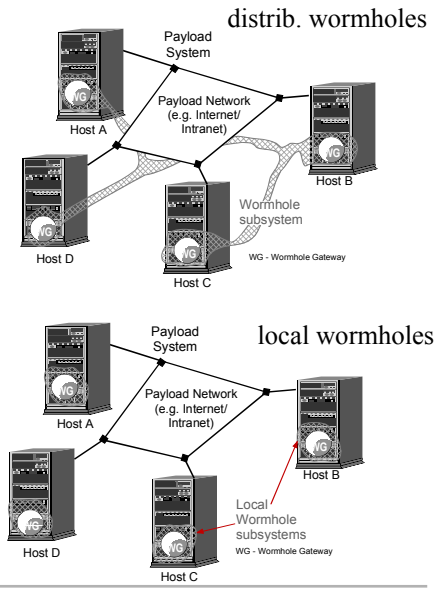
- *But how to control this process to our benefit?*

Guidelines

- Assume that *uncertainty is not ubiquitous* (and is not everlasting)--- the system has parts more predictable than others (and tends assume stable periods)
- Be *proactive in achieving predictability*--- make it happen at the right time, right place
- *Tolerate uncertainty* further to tolerating faults--- not all failures can be prevented, and some only on a probabilistic basis

Wormholes

- New design philosophy for distributed systems:
- constructs with privileged properties which endow systems with the capability of evading the uncertainty of the environment (``taking a shortcut'') for certain crucial steps of their operation, in order to achieve the required "hard properties" (predictability)



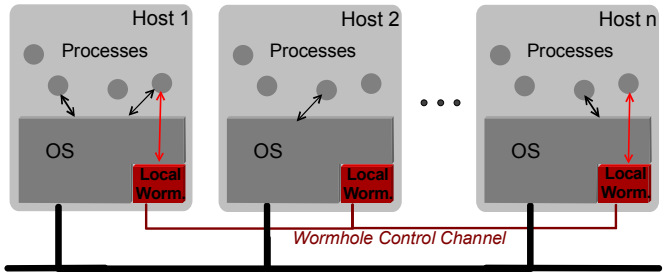
Characterisation of a Wormhole

- The little part that offers 'hard' properties, e.g.:
  - synchronous: bounds on processing delays, drift rate of local clocks and delivery delay of control messages
  - secure: trusted to be tamperproof, secure processing and comms.
- Small, simple and uses few resources
  - Easier to construct and verify, with high coverage
  - Supplies simple services, like failure detection, timely execution, trusted channels, or signatures
- Acts as a coverage amplifier for the whole system

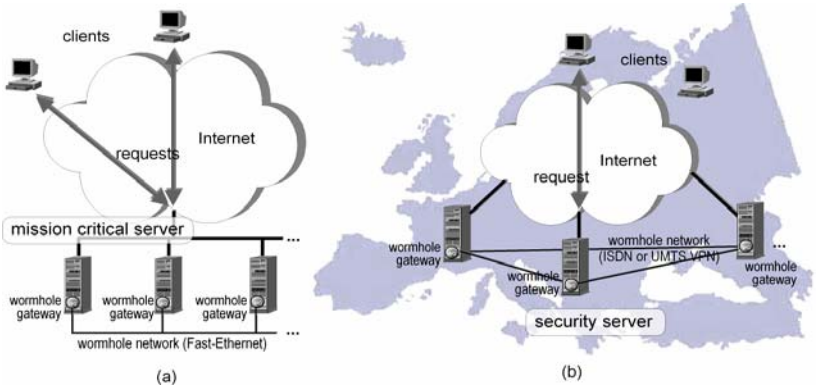
A small part of the system executes a small but critical part of its operation (a number of critical tasks) with high confidence (coverage)

Concrete examples

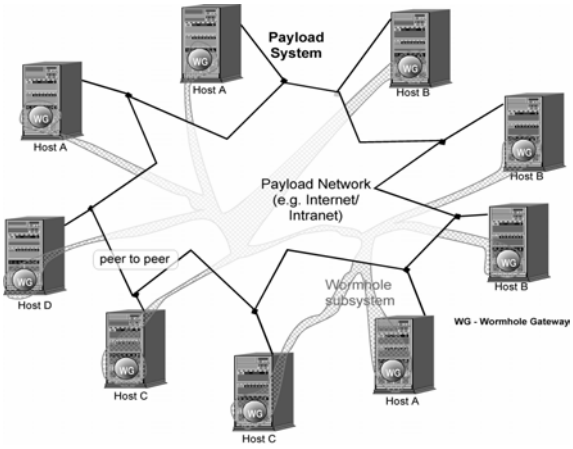
- We have played recently with two types of wormhole subsystems, to prove the concept:
  - Timely Computing Base for timeliness
  - Trusted Timely Computing Base for timeliness and security



Example of deployment of systems with wormholes



Example of deployment of systems with wormholes



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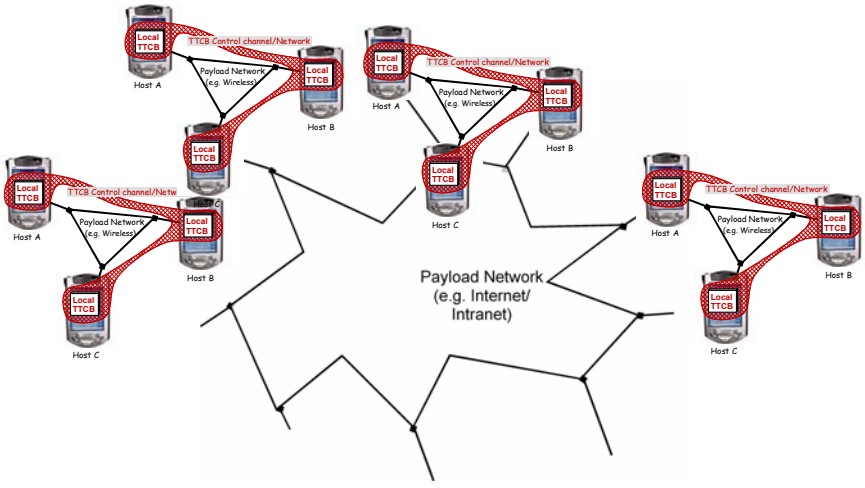
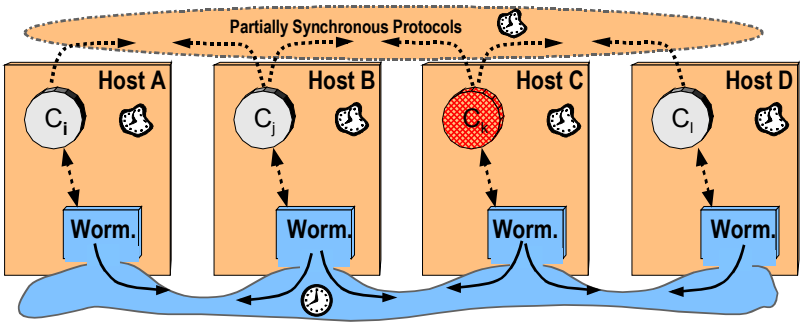
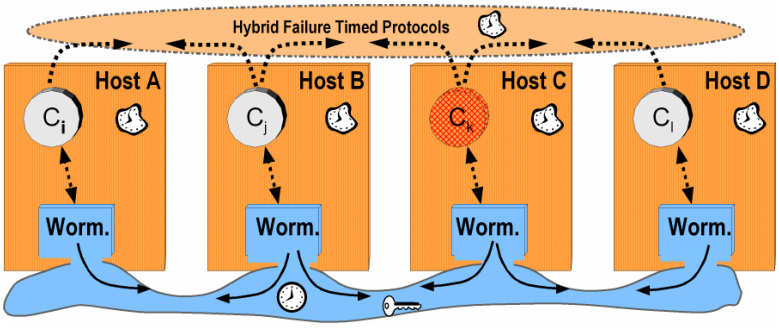


Strategy for timeliness awareness and/or assurance



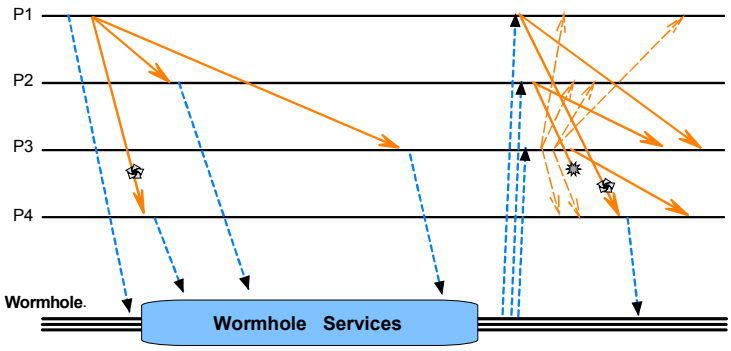
- - Fully synchronous, timely
- - Partially synchronous, potentially untimely

Strategy for security awareness and/or assurance



- - Fully secure (tamperproof), timely
- - Malicious, potentially untimely

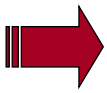
Rationale of the operation of Wormhole-aware protocols



A Concrete Model

(the timeliness wormhole example)

Timely Computing Base



TCB Model

TCB Services and Interface

Implementation of a TCB

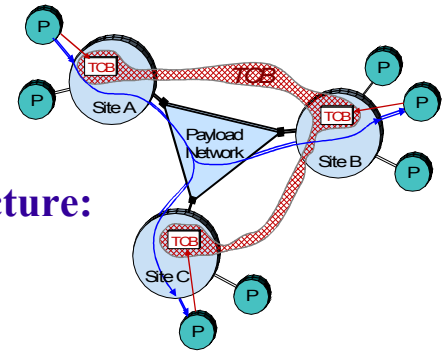
Quest for a Generic Solution

- How to encompass the entire spectrum of *synchrony,* from fully sync to fully async?
- How to enforce certain time-related properties rather than waiting for them to happen?

- We devised a model that encompasses the entire spectrum of *partial synchrony*
  - ☞ Timely Computing Base (TCB) Model
- We devised an architecture that enforces timeliness
  - ☞ Timely Computing Base (TCB) Architecture

The Timely Computing Base

- **Payload part:**
  - Where applications reside
  - Can have any degree of synchronism
- **Dual system architecture:**
  - Generic payload system
  - Control part: the TCB
- **Control part (TCB):**
  - Simple and small part of the system
  - Has known bounds on processing and message delivery delays



Why a new model

- None of the partial synchrony models is generic enough
  - each model treats synchrony asymmetries in it own way, relying on the evolution of synchrony with time, or with space, or both
  - neither can handle the whole synchrony spectrum
  - they tie application styles & semantics in one way or another

Why a new model (cont.)

- Timely Computing Base wormhole model :
  - ☞ postulates space-domain heterogeneity (vis-a-vis synchronism)
    - – ∃ components with "better" properties
  - ☞ monitors time-domain heterogeneity (synchrony variations)
    - – payload can have any synchronism
- Timely Computing Base architecture :
  - ☞ enforces architectural hybridization
    - – construction of the "better" components
  - ☞ enforces sync/async interface
    - – payload enjoying "better" components services

The conceptual "SYNC" toolbox

- TE – timely execution (simple or generic)
- DM – duration measurement (local or distr)
- CFD – crash failure detection (local or distr)
- TFD – timing failure detection (local or distr)

Alternative models

- Interesting applications for unrestrained failure modes require a perfect failure detector [Guerraoui02]
- A fully synchronous subsystem is required to implement a pFD [Chandra96]
- Weakest of known timed system is TA, but no pFD possible on strict TA
- Consider TA+SYNC, with simplest set of services: simpleTE, local DM
- Consider applications where slow nodes do *harakiri:*
  - Tout => Crash Failure (CF)
  - Tout => Local DM
  - *enforce*(Crash) => simpleTE
  - This version of TA+SYNC(simpleTE,locDM) can be implemented with a watchdog (WD)
  - pFD is achieved, through the transformation Tout => enforce(Crash), and some algorithmics to ensure that any P crashes before being suspected [Fetzer01]
- Consider applications that survive timing faults in one process and/or fail-safe requires orderly shutdown routines, and not just WD 'click'
- Then: WD is not generic TE, and Tout => *enforce*(Crash) is not acceptable

Alternative models

- Consider TA+SYNC(genTE, distrDM)
  - That is, we implement distr DM inside SYNC, gaining in precision and separation of concerns; we implemente generic timely execution
  - At this point, we can build pCFD inside the SYNC box
- Now we have TA+SYNC(genTE,distrDM, pCFD):
  - we can run all interesting non-timed applications
  - but can we build timely applications, even soft? No.
- Consider RT+SYNC(genTE, distr DM, distr pCFD):
  - Can we build timely appl's? Not generically, we need timing failure detection [Veríssimo99]
- Consider AnySyn+SYNC(genTE, distr DM, distr pTFD):
  - We can build any applic. from time-free to RT payload with the same model
  - A world of timed/timely applications opens
- Fully-fledged SYNC toolbox = TCB : gen TE, distr DM, distr TFD

Architecture and coverage

- How to build a SYNC toolbox, aka Timely Computing Base?
- Suppose environment with 't' parameters, and protocol 'P' which uses 't' directly, deriving property-level Tp [TTP, Cristian]
- If 't' is violated, P fails, sometimes not only timeliness properties, but also safety properties
- Suppose now environment with 't' parameters, and protocol 'P' which is implicitly indexed to 't'
- That is, P is time-free by construction, and there is a time complexity equation indexed to 't'
- P is *immersed* in the environment, and from there, actual values are derived for Tp [LeLann,AMp]

Achieving Synchronism by immersion

- How to achieve synchronism with a timer-driven ("async") protocol, given that classical approaches to synchronous protocols are clock-driven ("sync") [Cristian]?:
  - achieve and determine upper bounds on frame delivery delays by the abstract network, in the presence of ~~[illegible]~~
  - impose a performance specification on the NAC hardware/software (CPU, kernel, etc.) in order that processing times of the protocol actions are bounded, and known for the worst case traffic pattern specified;
  - structure the protocol in phases, so that an execution predictably has a bounded number of phases, clearly delimit phases, in what concerns error detection/recovery (omission and timing), and permanently ~~[illegible]~~ bounds);
  - structure each phase as a series of timed-out transmissions-with-response, so that it can be decomposed in time, in ~~[illegible]~~ deliveries and protocol actions as specified above, having thus with a known duration bound.

SYNCHRONISM OF ENVIRONMENT
TIME-FREE PROTOCOL STRUCTURE
IMMERSION

- With these measures, AMp execution time would be bounded to a known value [VeríssimoSRDS90]

Architecture and coverage

- Immersion is a good conceptual move, but ...
- Observe what happens when ‘t’ varies:
  - ☞ Protocols which have no timeliness properties will move faster or slower, depending on ‘t’; they will always be safe.
  - ☞ Protocols with timeliness (real-time) properties indexed by immersion to a given magnitude of ‘t’, will give timing failures when ‘t’ increases, violating timeliness.
  - ☞ Protocols whose safety properties depend on the environment being synchronous (‘t’ being respected) will fail on ‘t’ changing.

Architecture and coverage

- In the past discussion, there were two crucial protocols whose safety requires a fully sync environment (‘t’ not failing): pCFD and pTFD
- Any appl. running these protocols on the same environment used by normal (payload) protocols, has a coverage problem for a start:
  - ☞ The whole system is complex, so coverage comes down
  - ☞ How do we enforce ‘t’ for complex systems? ☹

Architecture and coverage

- Suppose the system is hybrid with regard to fault and synchrony
  - Payload: any synchrony, indulgent w.r.t. 't_P' of the environment
  - Control: fully synchronous, strict w.r.t. 't_C' of the environment
  - It is built through architectural hybridization:
    - the part of the environment supplying 't_C' is specially built: we do get 't_C'!
    - the rest (payload) is normal stuff: 't_P' is not so assured
- Build control algorithms (ex., pCFD, pTFD) on control part
- Immerse payload algorithms (e.g. time-free) into the 't_P' environment.
- 't_P' hypothesis may fail, but can be detected by control (ex., pCFD, pTFD) with high assurance (of 't_C')

Dependability framework for adaptivity

Dependability framework for adaptivity

- Restate 'correctness' definition:
  - Consider normal and critical properties
  - Normal properties can be violated within rules
  - Critical properties cannot
- Define behaviour classes:
- Adaptive
  - Recurrent violation of a normal property is accepted, with a bounded probability
- Safe
  - Occasional violation of a normal property is accepted, its up to the system to react (e.g. using conventional fault tolerance)
- Fail-safe
  - Any violation of a property is not acceptable, the system must stop

What is the philosophy?
(time domain example)

- Timing failures more complex than they look
  - **Unexpected delay** - "normal" effect
  - **Contamination** (of safety props) - error propagation effect
  - **Decreased coverage** - continued (statistical) effect
- Can we achieve correct operation despite these?
  - Contamination should be avoided at all cost
  - Coverage should remain stable

Why is the framework generic

- Generic properties dictate correctness of applications, regardless of functional semantics
  - **Coverage Stability -** coverage of timing assumptions remains stable
  - **No-Contamination -** safety properties not violated
- Under uncertain timeliness, different classes of appl's secure these properties in different ways
- It is necessary to detect timing failures, and react to that

TIMING FAILURE DETECTOR (TFD) considered fundamental

Dependable and Adaptive Computing with a TCB wormhole

- Introduce classes of applications that deal with these problems when assisted by a TCB:
  - Fail-safe: exhibits correct behaviour or stops in fail-safe state
  - Time-elastic: exhibits coverage stability
  - Time-safe: exhibits no-contamination
- Apply known fault tolerance techniques to the application classes (or combinations thereof):
  - detection and/or recovery; masking
- *The TCB Model and Architecture* [ieeeTOCS2002]

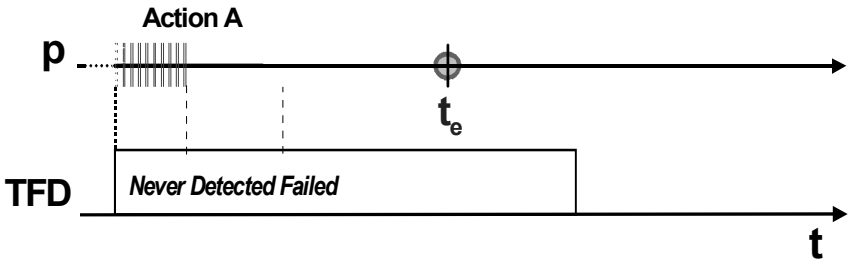
Example application frameworks

- Fail-safe operation [DSN2000] :
  - by switching to a fail-safe state after the first failure
  - requires the TFD service and appl´s to be of the fail-safe class
- Reconfiguration and adaptation [SRDS2001] :
  - by enforcing coverage stability
  - requires appl´s to be of the time-elastic and time-safe class
- Timing error masking [DSN2002]:
  - by using replication to mask transient timing errors
  - requires the TFD service and appl´s to be time-safe class

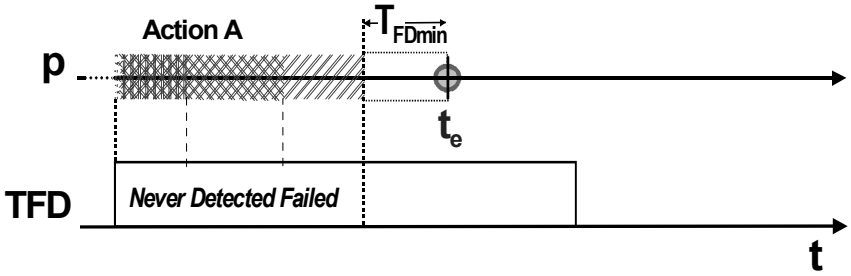
Timing Failure Detection

- Timing Failure:
  - ☞ Given the execution of a timed action X specified to terminate until real time instant te, there is a timing failure at p, iff the termination event takes place at an instant t'e, te < t'e ≤ ∞
- Timing Failure Detection:
  - ☞ **Timed Strong Completeness:** *There exists* TTFDmax *such that given a timing failure at* p *in any timed action, the TCB detects it within* TTFDmax *from* te
  - ☞ **Timed Strong Accuracy:** *There exists* TTFDmin *such that any timely timed action that does not terminate within -* TTFDmin *from* te *is considered timely by the TCB*

Timing Failure Detection



Timing Failure Detection



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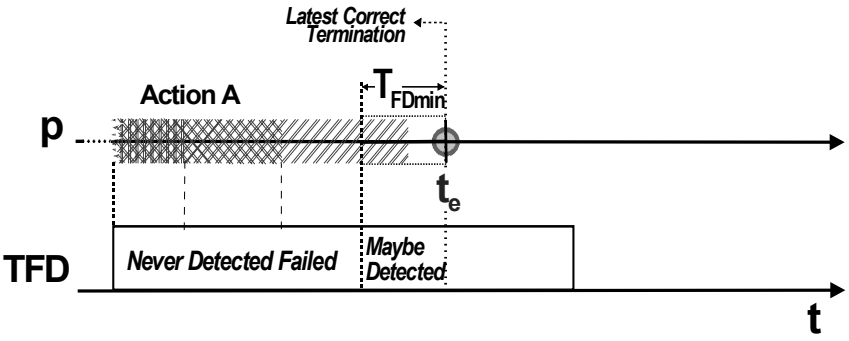

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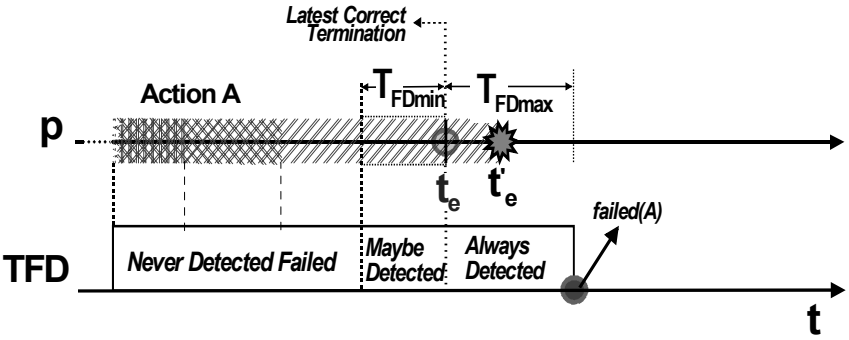

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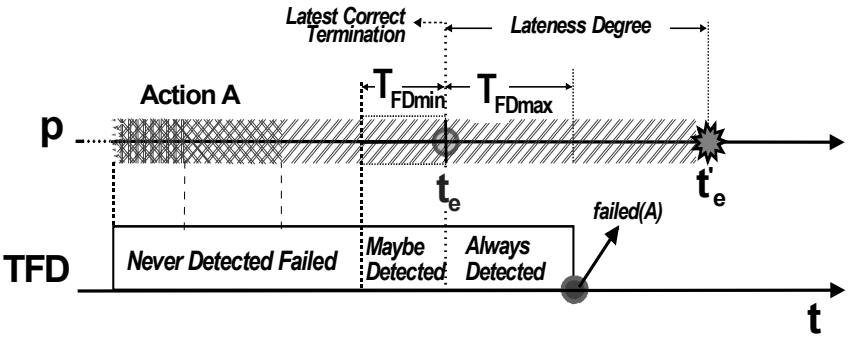


TCB Model

TCB Services and Interface

Implementation of a TCB

Services and API of the TCB

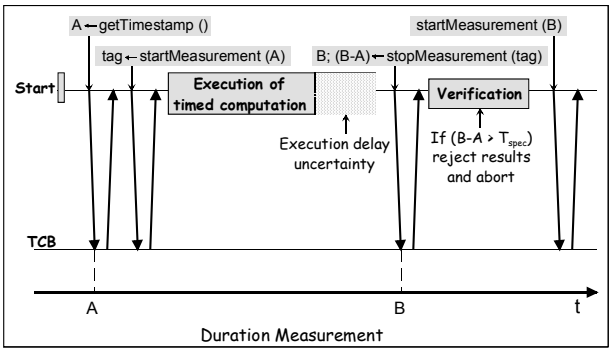
- The TCB provides minimal services:
  - TE - Timely execution
  - DM - Duration measurement
  - TFD - Timing failure detection
- And a payload-to-TCB interface
  - Allows potentially asynchronous applications to dialogue with a synchronous component

Synch/Asynch Interface

- Important issues to retain:
  - The TCB does not make applications timelier
  - Service invocation latency not bounded
  - Service responses or timing failure notifications not bounded
  - Nothing obliges applications to become aware of failures
- The TCB as an oracle:
  - Applications take advantage of the TCB by construction
  - They observe correctness of past steps before proceeding
  - Timeliness always observed in terms of durations
  - Time-critical responses to failures handled by the TCB

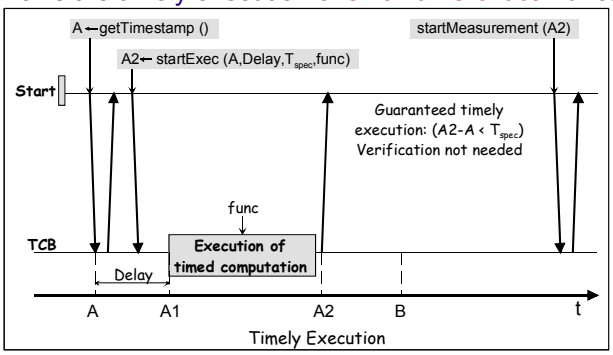
API

- Duration Measurement
  - ☞ Allows the measurement of upper bounds of payload actions



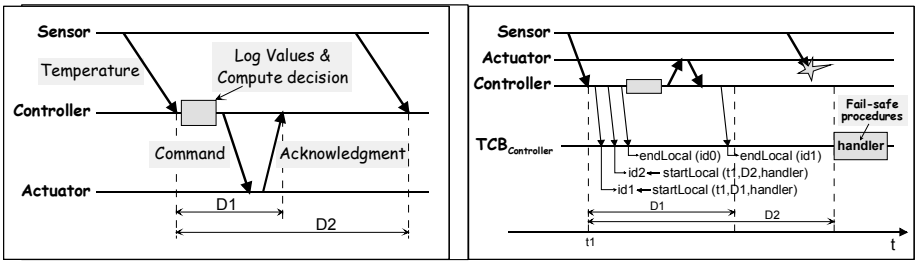
API

- Timely Execution
  - ☞ Allows the timely execution of small time-critical functions



API

- Timing Failure Detection
  - Allows detection of timing failures (of local and distributed actions)
  - Allows timely execution of safety procedures upon the detection of a timing failure



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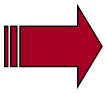
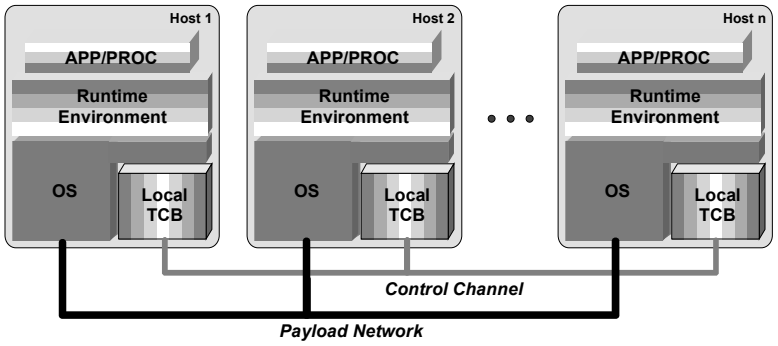


Implementation of a TCB

Implementation Issues

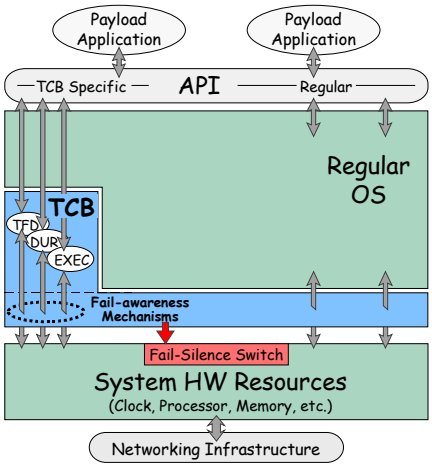
- Duration measurement
  - Local durations: local clock
  - Distributed durations: round-trip duration measurement technique
- Timely execution
  - Small functions residing in the TCB address space
  - Use known techniques of real-time systems
    - Admission control, schedulability analysis, WCET calculation
- Timing failure detection
  - Distributed protocol to ensure (Timed) Completeness and Accuracy
  - Set up timeouts using timers (based on local clock)

A concrete example



A System with a TCB

- The TCB is built with given <*bound,coverage*> pairs
- Hardware and inter-TCB communication channel may assume different forms, for different <*bound,coverage*> pairs
- Software kernel on a plain desktop (PC or workstation) may be used



Conclusions

- Some achievements...
- (T)TCB wormhole prototypes
  - Software Available at http://www.navigators.di.fc.ul.pt/software/tcb
- Timing fault tolerance for event-based systems
- Byzantine-resilient reliable multicast
- In preparation: Byzantine-resilient consensus, atomic multicast and membership
- See more at: www.navigators.di.fc.ul.pt -- “Documents”

Some Recent Publications

- See more at: www.navigators.di.fc.ul.pt -- "Documents"

- *Traveling through wormholes: Meeting the grand challenge of distributed systems*. Paulo Veríssimo. In Proceedings of the International Workshop on Future Directions in Distributed Computing, pages 144–151, June 2002
- *The Timely Computing Base Model and Architecture*. P. Veríssimo, A. Casimiro. Transactions on Computers - Special Issue on Asynchronous Real-Time Systems, vol. 51, n. 8, Aug 2002
- *The Design of a COTS Real-Time Distributed Security Kernel*. Miguel Correia, Paulo Veríssimo, Nuno Ferreira Neves. 4th EDCC, Toulouse, France, October 2002
- *Efficient Byzantine-Resilient Reliable Multicast on a Hybrid Failure Model*. Miguel Correia, Lau Cheuk Lung, Nuno Ferreira Neves, Paulo Veríssimo. 21st Symposium on Reliable Distributed Systems, Suita, Japan, October 2002
- *Generic Timing Fault Tolerance using a Timely Computing Base*. António Casimiro, Paulo Veríssimo. Proceedings of the International Conference on Dependable Systems and Networks, Washington D.C., USA, June 2002
- *Using the Timely Computing Base for Dependable QoS Adaptation*. António Casimiro, Paulo Veríssimo. Proceedings of the 20th IEEE Symposium on Reliable Distributed Systems, New Orleans, USA, October 2001
- *CORTEX: Towards Supporting Autonomous and Cooperating Sentient Entities*. Paulo Veríssimo, V. Cahill, António Casimiro, K. Cheverst, A. Friday, J. Kaiser. Proceedings of European Wireless 2002, Florence, Italy, February 2002