Self-Stabilizing Synchronization Of Arbitrary Digraphs In Presence Of Faults

Mahyar R. Malekpour

http://shemesh.larc.nasa.gov/people/mrm/

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What Is Synchronization?

- Local oscillators/hardware clocks operate at slightly different rates, thus, they drift apart over time.
- Local logical clocks, i.e., timers/counters, may start at different initial values.
- The synchronization problem is to adjust the values of the local logical clocks so that nodes achieve synchronization and remain synchronized despite the drift of their local oscillators.

- Application – Wherever there is a distributed system

Why is this problem difficult?

- Design of a fault-tolerant distributed real-time algorithm is extraordinarily hard and error-prone
  - Concurrent processes
  - Size and shape (topology) of the network
  - Interleaving concurrent events, timing, duration
  - Fault manifestation, timing, duration
  - Arbitrary state, initialization, system-wide upset

- It is notoriously difficult to design a formally verifiable solution for self-stabilizing distributed synchronization problem.

Characteristics Of A Desired Solution

- Self-stabilizes in the presence of various failure scenarios.
  - From any initial random state
  - Tolerates bursts of random, independent, transient failures
  - Recovers from massive correlated failures
- Convergence
  - Deterministic
  - Bounded
  - Fast
- Low overhead
- Scalable
- No central clock or externally generated pulse used
- Does not require global diagnosis
  - Relies on local independent diagnosis
- A solution for $K = 3F+1$, if possible, otherwise, $K = 3F+1+X$, $(X = ?) \geq 0$

and,

must show the solution is correct.

Formal Verification Methods

- Formal method techniques: **model checking**, **theorem proving**
- Use a model checker to verify a possible solution insuring that there are no false positives and false negatives.
  - It is deceptively simple and subject to abstractions and simplifications made in the verification process.
  - State space explosion problem
  - Tools require in-depth and inside knowledge, interfaces are not mature yet
  - Modeling a real-time system using a discrete event-based tool
- Use a theorem prover to prove that the protocol is correct.
  - It requires a paper-and-pencil proof, at least a sketch of it.

Alternatively …

- Find a simpler solution
- Reduce the problem complexity by reducing its scope or restricting the assumptions
- Wait for a more powerful model checker
  - 64-bit tool utilizing more memory
  - Faster and more efficient model checking algorithm

The Big Picture

- Solve the problem in the absence of faults.
- Learn and revisit faulty scenarios later on.

Fault Spectrum

Simple fault classification:

1. None
2. Symmetric
3. Asymmetric (Byzantine)

The OTH (Omissive Transmissive Hybrid) fault model classification based on *Node Type* and *Link Type* outputs:
(http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100028297_2010031030.pdf)

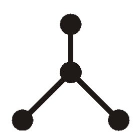
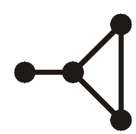
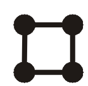
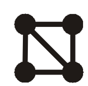
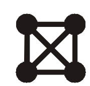
1. Correct (None)
2. Omissive Symmetric
3. Transmissive Symmetric (Symmetric)
4. Strictly Omissive Asymmetric
5. Single-Data Omissive Asymmetric
6. Transmissive Asymmetric (Byzantine)

What About Topology?

- What should the graph look like?
  - Graphs of interest: single ring, double ring, grid, bi-partite, etc.
  - Possible options (Sloane numbers/sequence):

K	1	2	3	4	5	6	7	8
Number of 1-connected graphs	1	1	2	6	21	112	853	11117

  - Example, for 4 nodes there are 6 different graphs:

					
Linear	Star/Hub	-	Ring	-	Complete

Where Are We Now?

- Have a family of solutions for detectably bad faults and $K \geq 1$ that applies to realizable systems.
  - Network impression and oscillator drift
- Have model checked a set of digraphs, NASA/TM-2011-217152
  - As much as our resources allowed (mainly, memory constrained)
- Have a deductive proof, NASA/TM-2011-217184
  - Concise and elegant

The Protocol

Synchronizer:	Monitor:
E0: if (*LocalTimer* < 0) *LocalTimer* := 0, E1: elseif (*ValidSync()* and (*LocalTimer* < *D*)) *LocalTimer* := γ, *// interrupted* E2: elseif ((*ValidSync()* and (*LocalTimer* $\geq T_S$)) *LocalTimer* := γ, *// interrupted* Transmit *Sync*, E3: elseif (*LocalTimer* $\geq P$) *// timed out* *LocalTimer* := 0, Transmit *Sync*, E4: else *LocalTimer* := *LocalTimer* + 1.	**case (message from the corresponding node)** {Sync: ValidateMessage() Other: Do nothing. } // case

How The Protocol Works

1. If someone is out there – accept its ***Sync*** message and relay it to others,

2. If no one is out there (or they are too slow) – take charge and generate a new ***Sync*** message,

3. Ignore – reject all ***Sync*** messages while in the ***Ignore Window***.
   - Rules 1 and 2 result in an endless cycle of transmitting messages back and forth
   - The *Ignore Window* properly stops this endless cycle

Key Results

Global Lemmas And Theorems

How do we know when and if the system is stabilized?

- **Theorem *Convergence*** – *For all $t \geq C$, the network converges to a state where the guaranteed network precision is π, i.e., $\Delta_{Net}(t) \leq \pi$.*
- **Theorem *Closure*** – *For all $t \geq C$, a synchronized network where all nodes have converged to $\Delta_{Net}(t) \leq \pi$, shall remain within the synchronization precision π.*
- **Lemma *ConvergenceTime*** – *For $\rho \geq 0$, the convergence time is $C = C_{Init} + \lceil \Delta_{Init}/\gamma \rceil P$.*
- **Theorem *Liveness*** – *For all $t \geq C$, LocalTimer of every node sequentially takes on at least all integer values in $[\gamma, P-\pi]$.*

Key Results

Local Theorem

How does a node know when and if the system is stabilized?

- **Theorem *Congruence*** – *For all nodes N_i and for all $t \geq C$, (N_i.LocalTimer(t) = γ) implies $\Delta_{Net}(t) \leq \pi$.*

Key Aspects Of Our Deductive Proof

1. Independent of topology
2. Realizable systems, i.e., $d \geq 0$ and $0 \leq \rho << 1$
3. Continuous time

Model Checked Cases

K	**Topology** (all links bidirectional)	**Topology** (digraphs)
2	1 of 1	1 of 1
3	2 of 2	5 of 5
4	6 of 6	83 of 83
5	21 of 21	Single Directed Ring 2 Variations of Doubly Connected Directed Ring
6	112 of 112	-
7	Linear*	Linear*
7	Star*	Star*
7	Fully Connected*	Fully Connected*
7 (3×4)	Fully Connected Bipartite*	Fully Connected Bipartite*
7	Combo	4 of 4
7	Grid	-
7	Full Grid	-
9 (3×3)	Grid	-
15	Star*	Star*
20	Star*	Star*

More Results

- Our family of solutions handles more than the no-fault (correct) case. It handles cases 1, 2, and 4 of the OTH fault classification. I.e., it is a fault-tolerant protocol as long as our assumptions are not violated and the faulty behavior does not violate our definition of digraph.
- Our family of solutions is an emergent system.

The OTH (Omissive Transmissive Hybrid) fault model classification based on *Node Type* and *Link Type* outputs:

1. Correct (None, No-fault)
2. Omissive Symmetric (Fail-detected, Fail-silent)
3. Transmissive Symmetric (Symmetric)
4. Strictly Omissive Asymmetric (1 or 2)
5. Single-Data Omissive Asymmetric
6. Transmissive Asymmetric (Byzantine)

Questions?