Fault-Tolerant

A Self-Stabilizing Synchronization Protocol For Arbitrary Digraphs

Mahyar R. Malekpour

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

PRDC 2011, December 12 – 14

Outline

- Synchronization
- Verification via formal methods
- Fault spectrum and complexity
- Where are we now and where are we going?

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
- How can we synchronize a distributed system?
- Under what conditions is it (im)possible?

A Brief History of Synchronization

- Norbert Wiener, mathematician
  - Author of the 1950 book Cybernetics: The Control and Communication in the Animal and the Machine
  - Brain waves, alpha rhythm, 1954
- Art Winfree, majored in engineering physics, wanted to be biologist
  - Modeled using runners on a track, synchronization in time and space, 1964
  - Topology was a ring
- Yoshiki Kuramoto, physicist
  - Introduced order parameter, synchronization in time, 1975
  - Topology was a ring
- Edsger W. Dijkstra, computer scientist
  - Presented (2 pg) the concept of self-stabilizing distributed computation, in 1973-1974.
  - Presented an algorithm for a ring

A Brief History of Synchronization

- Charlie Peskin, applied mathematician
  - Proposed self-organization idea (278 pg), in 1973-1975, while working on cardiac pacemakers.
  - Conjectured that there is a solution
  - Started to prove N-body systems of oscillators for large N
  - Ended with proof for two pulse-coupled oscillators by restricting the problem to its bare bone
- Steven Strogatz and Rennie Mirollo, mathematicians
  - Develop proof for N-pulse-coupled oscillators, 1989
  - Approach was simulation followed by mathematical proof for
    - Ideal case,
    - Ideal oscillators, and
    - Fully connected graph
  - Many publications, including a book entitled SYNC

for us

It all started with SPIDER, 1999

(Scalable Processor-Independent Design for Extended Reliability)

- Safety critical systems must deal with the presence of various faults, including arbitrary (Byzantine) faults

- **<u>Goals (in the presence and absence of faults):</u>**

1. Initialization from arbitrary state
2. Recovery from random, independent, transient failures
3. Recovery from massive correlated failures

What is known?

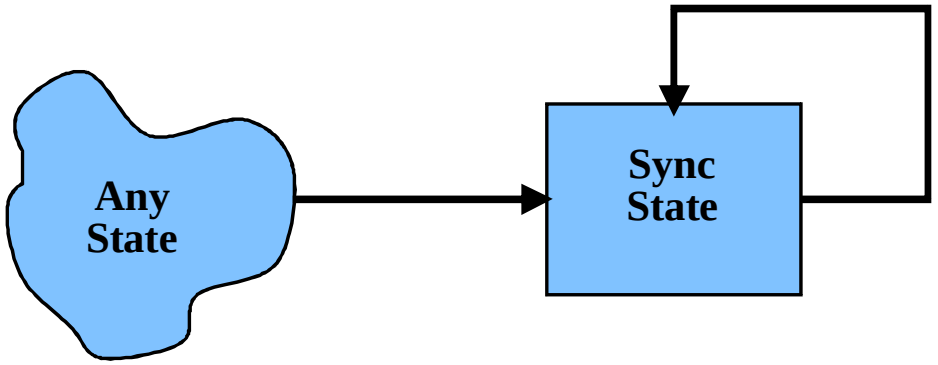
- Agreement can be guaranteed only if $K \geq 3F + 1$,
  - K is the total number of nodes and F is the maximum number of Byzantine faulty nodes.
  - E.g. need at least 4 nodes just to tolerate 1 fault.
- Periodic re-synchronization to prevent too much deviation in clocks/timers due to drift.
- There are many partial solutions based on strong assumptions (e.g., initial synchrony, or existence of a common pulse).
- There are clock synchronization algorithms that are based on randomization and are non-deterministic.
- There are claims that cannot be substantiated.
- There are no guidelines for how to solve this problem or documented pitfalls to avoid in the process.
- Speculation on proof of impossibility.
- There is no solution for the general case.

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.

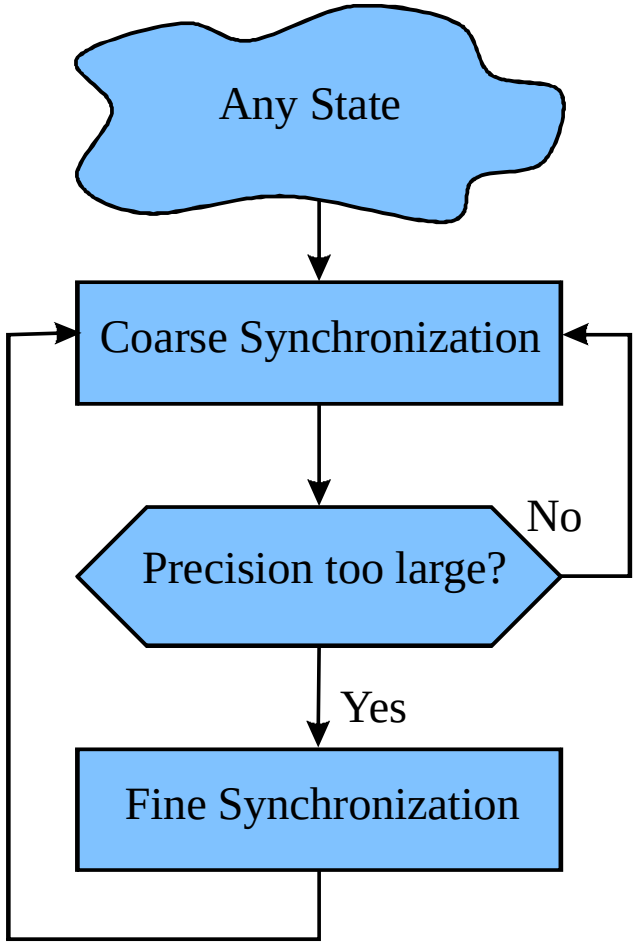
The Idea



- Keys: It is a feedback control system.
  It is a non-linear system.

- Bring all good nodes from any state to a known state.
  - *Convergence* property
- Maintain bounded synchrony.
  - *Closure* property

The interplay of *Coarsely* and *Finely Synchronized* protocols.



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.
- Use a theorem prover to prove that the protocol is correct.
  - It requires a paper-and-pencil proof, at least a sketch of it.

Bridging Two Worlds

- From simulation (VHDL) to model checking (SMV, SMART, UPPAL, NuSMV)

- From an engineer to a formal methods practitioner
  - I became a believer and an advocate; a formal methodist

- Found a partial solution in 2003, published in 2006
- Found another partial solution in 2007, published in 2009
- These solutions are for 4 nodes with one Byzantine fault and do not scale well to larger number of Byzantine faults
- Model checking of the first protocol took two years
- Model checking results are publically available

Model Checking

- Model checking issues
  - 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
- Intuitive solution is more memory and more computing power
  - PC with 4GB of memory running Linux, 32bit
  - There is a hardware limitation on the amount of memory that can be added to a given system
  - It may not eliminate/resolve state space problem
- 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

(Approach toward solving synchronization problem)

- Thus far, we've considered only the Byzantine faults and produced partial solutions.

- Change In Strategy
  - The shortest path between two points is not necessarily a straight line.
  - First, 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 (Omisive 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)

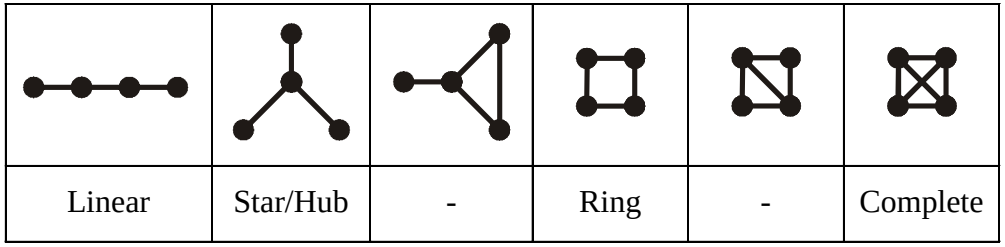
What about topology(*T*)?

- In the absence of faults, our previous two protocols work for graphs of any size.
  - Model checked for K ≤ 15
  - As long as the graph is fully connected

- What about other topologies? What should the graph look like?
  - Other 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

Sloane A001349

n	a(n)
0	1
1	1
2	1
3	2
4	6
5	21
6	112
7	853
8	11117
9	261080
10	11716571
11	1006700565
12	164059830476
13	50335907869219
14	29003487462848061
15	31397381142761241960
16	6396956011322517617627 7
17	24587183168208402651952856 8
18	17873317252488990888902005765 80
19	24636021429399867655322650759681644

Synchronization

- What are the parameters?
  - Maximum number of faults, $F \geq 0$
  - Communication delay, $D > 0$ clock ticks
  - Network imprecision, $d \geq 0$ clock ticks
    - So, communication delay is bounded by $[D, D+d]$
  - Oscillator drift, $0 \leq \rho << 1$,
  - Number of nodes, i.e., network size, $K \geq 1$
  - Synchronization period, P
  - Topology, T

Realizable Systems

Scalability

- **Synchronization, S = (F, D, d, ρ, K, P, T)**

Where Are We Now?

- Have a family of solutions for $F = 0$ and $K \geq 1$ that apply to all of the following scenarios and encompass all of the above parameters.
  1. Ideal scenario where $\rho = 0$ and $d = 0$.
  2. Semi-ideal scenario where $\rho = 0$ and $d \geq 0$.
  3. Non-ideal scenario, i.e., realizable systems, where $\rho \geq 0$ and $d \geq 0$.

- 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
- Other researchers currently model checking graphs with more nodes and fewer abstractions than our model checking effort.

The Protocol

Synchronizer:

E0: if (*LocalTimer* < 0)
LocalTimer := 0,

E1: elseif (*ValidSync()* and (*LocalTimer* < *D*))
LocalTimer := *γ*, // *interrupted*

E2: elseif ((*ValidSync()* and (*LocalTimer* ≥ T_S))
LocalTimer := *γ*, // *interrupted*
Transmit *Sync*,

E3: elseif (*LocalTimer* ≥ *P*) // *timed out*
LocalTimer := 0,
Transmit *Sync*,

E4: else
LocalTimer := *LocalTimer* + 1.

Monitor:

case (message from the corresponding node)
{Sync:
ValidateMessage()
Other:
Do nothing.
} // case

How Does It Work?

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*

Variations Of The Protocol

- **It is a family of solutions**

- **Reset**

  in E1 and E2:

  ~~*LocalTimer* := γ, // interrupted~~

  LocalTimer := *0*, // interrupted

- Reduced precision, $\Delta_{ij} = \gamma$, $\Delta_{InitGuaranteed} = W\gamma$
- Ripple effect
- Same usable range $[\gamma, P - \pi]$

Variations Of The Protocol

- **Jump Ahead**

  in E1 and E2:

  ~~*LocalTimer* := γ, // interrupted~~

  LocalTimer := *LocalTimerIn* + γ, // interrupted

  if (*LocalTimer* ≥ *P*)

  LocalTimer := 0,

  in E2 and E3:

  ~~Transmit *Sync*,~~

  Transmit *Sync* and *LocalTimer*,

- Increased overhead (message size)
- More messages during convergence
- Better precision, $\Delta_{InitGuaranteed} = (1+d)\delta(P)$
- Less usable range $[W\gamma, P - \pi]$

Variations Of The Protocol

- Recall, $S = (F, D, d, \rho, K, P, T)$
- The general form, **dynamic digraph**, $S' = (F, D, d, \rho, K(t), P, T(t))$
  - $K(t)$ represents the **dynamic node count** at time t
  - $T(t)$ represents the **dynamic topology** for a given $K(t)$
- Dynamic Node Count – the number of nodes comprising the network can change at any time.
- Dynamic Topology – the number of links can change at any time.
- Dynamic Digraph – once synchrony is achieved, the system maintains its synchrony provided that the new nodes enter the network from a reset state.

More Results, In Retrospect

- 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.
- In retrospect, “fault-tolerant” should be included in the paper’s title.
- Our family of solutions is an emergent system.

The OTH (Omisive 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)

Status and Issues

- Our deductive proof is documented and publically available. There is still a need for this solution to be analyzed in a more mathematically rigorous way.

- Is there a better way to prove that the protocol is correct?
- How to verify the proofs?
- To model check or to theorem prove?
  - If neither, then what?
  - If model check, then how to model check all topologies?
- Any volunteers?

Where are we going?

- At the end, we are defining the path from one end of the fault spectrum to the other; from No Fault to Byzantine Faults and solving the synchronization problem for the general case, i.e., for all topologies and fault types.

- We envision a final general/unifying solution encompassing all topologies and fault types.

- Note that thus far the convergence time, *C*, seems consistent and, I believe, we are on the right track.

$$C_{Byzantine} = O(P)$$
$$C_{No\text{-}fault} = O(P)$$

Questions?