Technische Universität Braunschweig

Institut für Betriebssysteme und Rechnerverbund

Byzantine Agreement Service for Cooperative Embedded Systems

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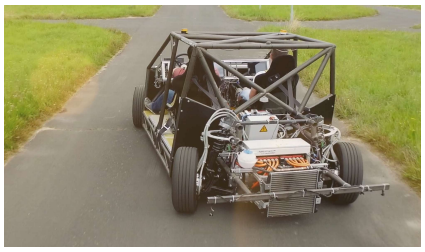
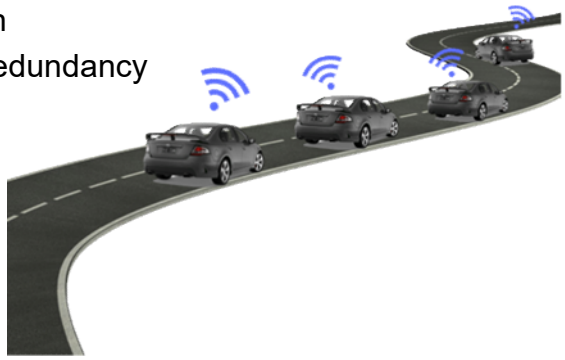
Controlling Concurrent Change

- Application domain: automotive and space
- Facilitate independent software/hardware updates on embedded system platforms
- Safety, security, availability
- www.ccc-project.org



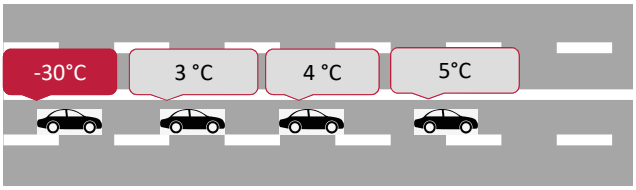
Motivation

- CCC second phase: distributed changes
- Cooperative agents coordination
  - Vehicle platooning, unmanned aerial vehicle swarms, robots etc.
  - Self-perception, self-action
- Joint view and action
- Share information, redundancy



Motivation

- Cooperation=efficiency? Redundancy=reliability?
- Nodes might behave differently
  - Objective factors: position, environment, configuration
  - Faulty behaviors: transient sw/hw error, communication failure, malicious attack



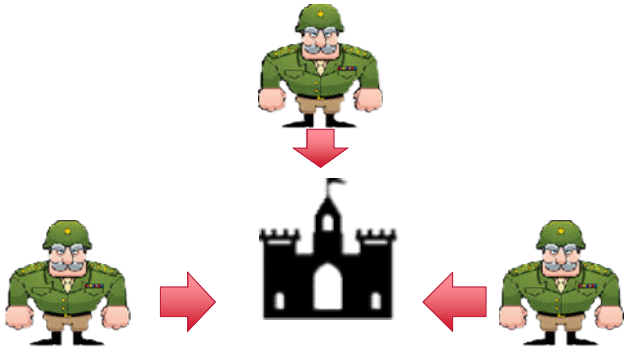
Motivation

- Popular approach: convergence based
- Less explored: distributed agreement algorithm
  - Explicit termination criterion (undecided ➔ decided)
  - Guarantee of exact consensus
  - Well tailored for small groups

Outline

- An introduction to Byzantine fault tolerance
- Making an agreement
- Trusted subsystem
- Evaluation
- Conclusion and future work

Byzantine General Problem [2]



- Honest generals and traitors
- Byzantine faults: not only crash

[2] Lamport, L.; Shostak, R.; Pease, M. (1982). "The Byzantine Generals Problem" (PDF). ACM Transactions on Programming Languages and Systems. 4 (3): 382–401.

Byzantine General Problem

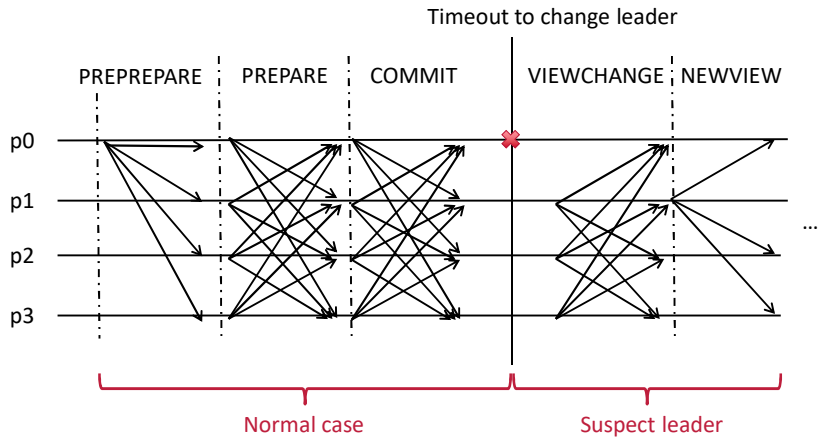
n=3
f=1

???

n≥3f+1 to tolerate f traitors

!>

PBFT Algorithm [3]



[3] Miguel Castro and Barbara Liskov. "Practical Byzantine fault tolerance and proactive recovery". In: *ACM Trans- actions on Computer Systems* 20.4 (2002), pp. 398–461.

PBFT Algorithm

- Mainly designed for state machine replication
  - Powerful machines in data center
  - Simply takes leader's proposal, seldom involves local non-deterministic values (sensor value) *

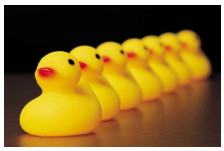
* Briefly discussed in PBFT paper

Outline

- An introduction to Byzantine fault tolerance
- Making an agreement
- Trusted subsystem
- Evaluation
- Open questions

Agree … on what?

- Follow-command: only leader proposes
  ➔Can directly use PBFT algorithm



- Consensus: everyone has its own value
  - Discrete: binary decision, leader election, etc.
  - Continuous: sensor value

Fault model: who and what can go wrong

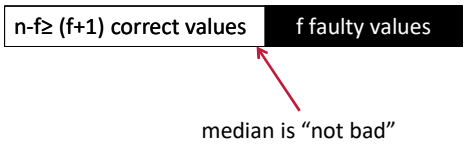
- A group of nodes (n=4 as an example)
- f<n/3 nodes can be faulty (f=1 in the example)
  - Typical Byzantine faults (crash, bit-flip, package loss, malicious behavior etc.)
  - Wrong sensor value

  ➔Even an “intended-to-be-honest” node might be fooled by its mal-functional sensor

  ➔Validity issue: cannot take just a value from single node

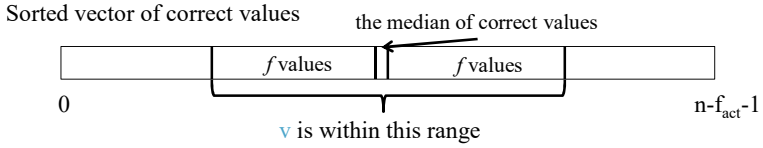
Validity of sensor values

- Value exchange before agreement
  - Broadcast own value
  - Leader collects as many values as possible (at most n-f)
  - Sort and choose the median
- When n ≥ 3f+1



Validity of sensor values

- Collect any (n-f) values, choose the median
- Median validity [8]: the chosen value v is close to the median of all correct values (unknown to algorithm)



$$Sorted\_Correct[index_{med} - f] \leq v \leq Sorted\_Correct[index_{med} + f]$$

- Already a tight bound in asynchronous system.

[8] Stolz, David, and Roger Wattenhofer. "Byzantine Agreement with Median Validity." *LIPIcs-Leibniz International Proceedings in Informatics*. Vol. 46. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, 2016.

Validity of sensor values

n=4, f=1, f_{act}=1

Node	A	B	C	D
Measured temperature	3	4	5	X Byzantine!

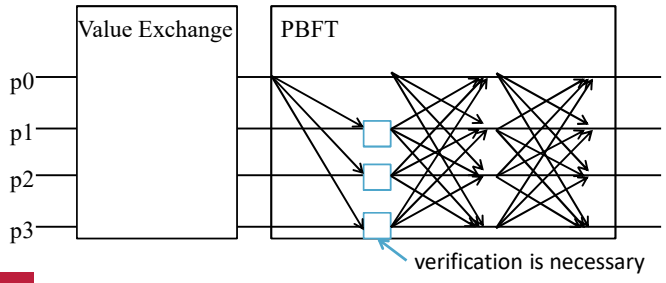
Some possible cases:

C is slow	-30	3	4
A is slow	-30	4	5
B is slow	3	5	+40
C is slow	3	3.5	4

3 ≤ valid value ≤ 5

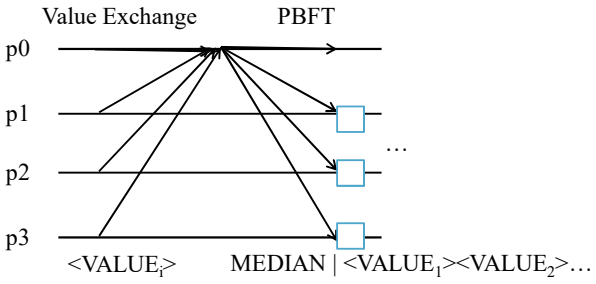
Agree on sensor value

- Value exchange phase + Agreement algorithm (PBFT)
- Requirement:
  - Leader proposes the median of (n-f) values …
  - … with a certificate, so that followers can verify



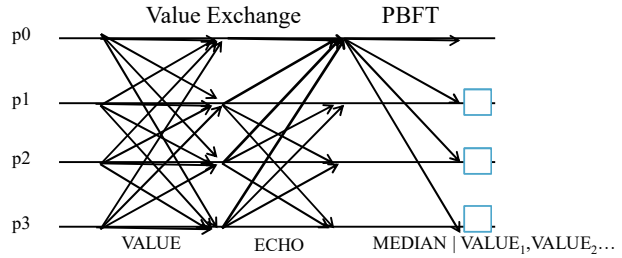
Sensor value agreement: solution 1

- With digital signature is trivial



Sensor value agreement: solution 2

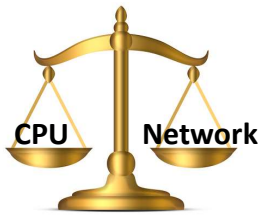
- Get rid of signature [4]:
  - Leader receives (2f+1) echoes of a value -> put it into certificate
  - Leader collects (n-f) values in certificate -> propose
  - Follower receives (f+1) corresponding echoes for every value in certificate -> accepts



[4] Milosevic, Zarko et al. "Unifying Byzantine consensus algorithms with weak interactive consistency." *International Conference On Principles Of Distributed Systems*. Springer Berlin Heidelberg, 2009.

Sensor value agreement

- The use of signature
  - ✓ One communication round less
  - ✗ Computationally expensive (for embedded systems)



Outline

- An introduction to Byzantine fault tolerance
- Making an agreement
- Trusted subsystem
- Evaluation
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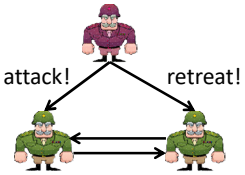
Background: recap

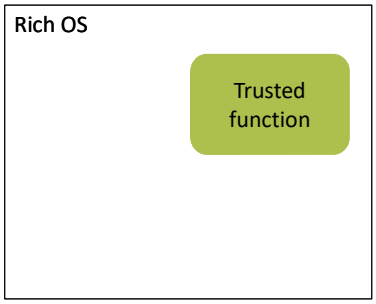
- Why 3f+1 nodes required?



- Equivocation: send different values to different recipients
- Can we restrict the ability of Byzantine nodes?

Trusted subsystem

- Assume a special part of system cannot go wrong
  - …except for crash faults
  - Hardware support in modern CPUs (ARM TrustZone, Intel SGX)



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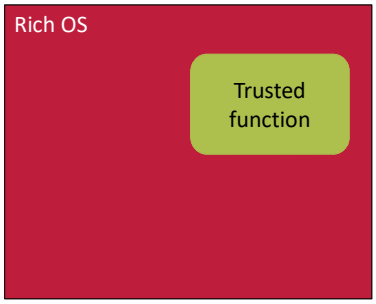


Trusted subsystem

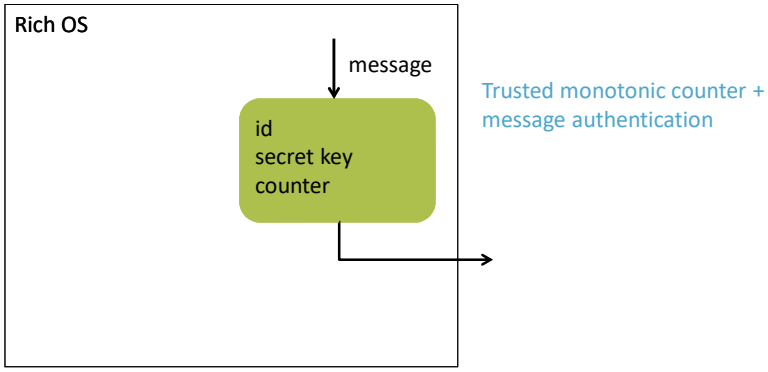
- As simple as possible
- …but powerful enough

- Trusted monotonic counter + message authentication
- Examples are MinBFT, CheapBFT, Hybster [5,6,7] etc.

[5] Giuliana Santos Veronese et al. “Efficient Byzantine Fault-Tolerance”. In: *IEEE Trans. Computers* 62.1 (2013), pp. 16–30.
[6] Rüdiger Kapitza et al. “CheapBFT: Resource-efficient Byzantine Fault Tolerance”. In: *Proceedings of the EuroSys 2012 Conference*. Ed. by European Chapter of ACM SIGOPS. Switzerland, 2012, pp. 295–308.
[7] Behl, Johannes et al. "Hybrids on Steroids: SGX-Based High Performance BFT." Proceedings of the Twelfth European Conference on Computer Systems. ACM, 2017.

Trusted subsystem

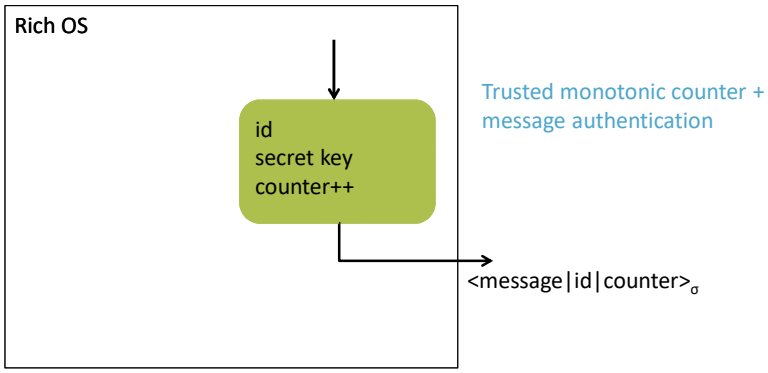
- All broadcast messages are certified by trusted counter



Trusted subsystem

- All broadcast messages are certified by trusted counter
- After certifying a message, counter increases by 1

➔Cannot use the same counter to certify two different messages

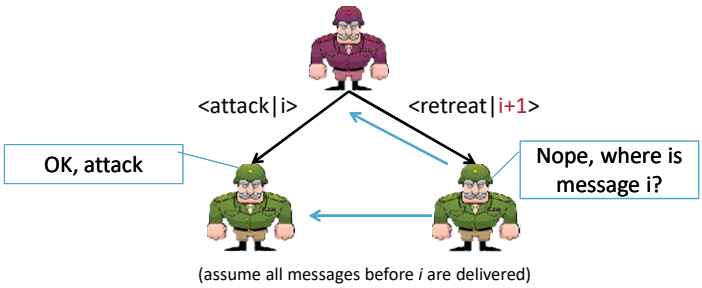


Trusted subsystem

- All outgoing messages are certified by trusted counter
- After certifying a message, counter increases by 1

➔Cannot use the same counter to certify two different messages

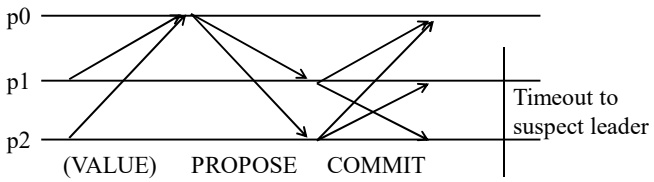
- Recipient knows the expected counter and can verify



(assume all messages before *i* are delivered)

Trusted subsystem

- Cannot equivocate anymore ➔ hybrid fault model
  - Only 2f+1 nodes needed
  - One less communication round



Trusted subsystem

- Cannot equivocate anymore ➔ hybrid fault model
  - Only 2f+1 nodes needed
  - One less communication round
- More benefit: avoid public-private key encryption

  $<message|id|counter>_{\sigma}$
  - Cannot use other's id to certificate
  - Key won't be leaked even to host OS
  - All trusted subsystems can share one secret key for broadcast

  ➔Assume static group, and keys are correctly distributed

Trusted subsystem: a remark of sensor value validity

- Validity issue: required n≥3f+1
  - Still (3f+1) value providers, but only (2f+1) voters, the others are passive learners
  - Or assume known sensor permissible error

Outline

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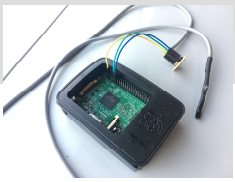
Experiment setting



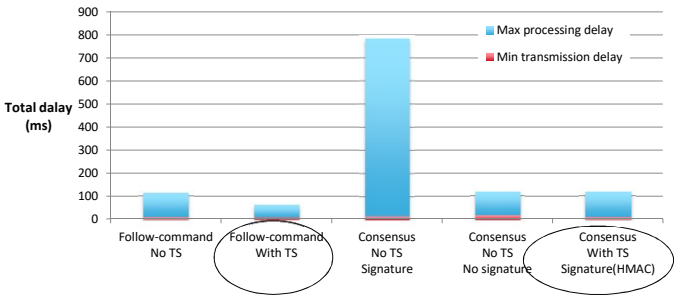
- 4 RaspberryPis
  - already support for ARM TrustZone…
  - …but as a preliminary work, we use a software simulation
  - Inject 2ms extra delay for each encryption operation [6]
- Ad-hoc wireless communication, ping ≈ 8ms
- Two agreement scenarios:
  - Follow-command: only leader proposes something
  - Consensus: everyone has its own value

  ➔Thermometer, reading time ≈ 850ms, not counted for agreement time

[6] Rüdiger Kapitza et al. "CheapBFT: Resource-efficient Byzantine Fault Tolerance". In: *Proceedings of the EuroSys 2012 Conference*. Ed. by European Chapter of ACM SIGOPS. Switzerland, 2012, pp. 295–308.

Experiment result

- Digital signature results in much higher delay
- Trusted subsystem is efficient in both scenarios



Outline

- An introduction to Byzantine fault tolerance
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- Conclusion and future work

Conclusion and future work

- Provide agreement-as-a-service for embedded systems
- Sensor value agreement with value validity
- Using trusted subsystem to decrease overhead
  - Reduce from 3f+1 to 2f+1 nodes, and one less message round
  - MAC instead of digital signature
- Next steps:
  - Implement trusted subsystem based on ARM TrustZone
  - Network stack support in target application
  - Real-time requirement
  - Compare & combine with convergence based approaches

Conclusion and future work

- Provide agreement-as-a-service for embedded systems
- Sensor value agreement with value validity
- Using trusted subsystem to decrease overhead
  - Reduce from 3f+1 to 2f+1 nodes, and one less message round

Thank you for your attention!

- Next steps:
  - More lightweight code base targeted for embedded system
  - Implement trusted subsystem based on ARM TrustZone
  - Network stack support
  - Real-time requirement
  - Comparison & combine with convergence based approaches

References

[1] W. Ren, R. W. Beard and E. M. Atkins, "Information consensus in multivehicle cooperative control," in *IEEE Control Systems*, vol. 27, no. 2, pp. 71-82, April 2007.

[2] Lamport, L.; Shostak, R.; Pease, M. (1982). "The Byzantine Generals Problem" (PDF). ACM Transactions on Programming Languages and Systems. 4 (3): 382–401.

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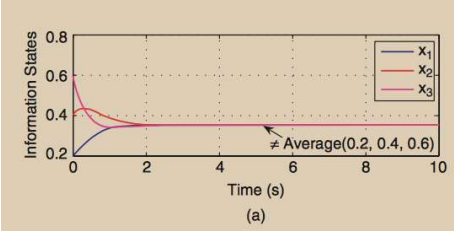
[8] Stolz, David, and Roger Wattenhofer. "Byzantine Agreement with Median Validity." *LIPIcs-Leibniz International Proceedings in Informatics*. Vol. 46. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, 2016.

Motivation

- Popular approach: convergence based



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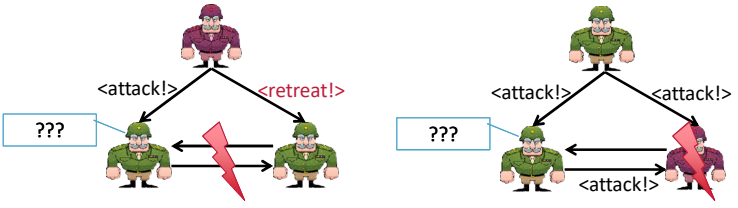
- Good scalability in large groups
- E.g. data fusion, speed control of platooning

Byzantine General Problems

- Asynchronous system



Byzantine fault tolerance

- Synchronous vs asynchronous system model
- Known results:
  - Synchronous system + message signature: n ≥ 2f+1 nodes
  - FLP impossibility: No consensus can be achieved in asynchronous system, even if only one node can crash.

  ➔Work around: algorithm runs without assuming synchrony, but has different guarantees under two conditions.
  - (Partially-) Asynchronous system: n ≥ 3f+1 nodes

Validity of sensor values

- Co
- Pr
- Th

n=4, f=1, f_{act}=0

Node	A	B	C	D
Measured temperature	3	4	5	6

Some possible cases:

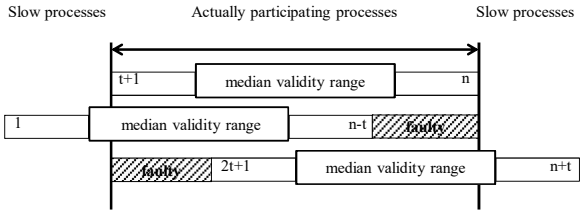
C is slow	3	4	6
A is slow	4	5	6
B is slow	3	5	6

↑

3 4 ≤ valid value ≤ 5

An explain of tight bound

- Run the same algorithm 3 times
- The same value should be decided



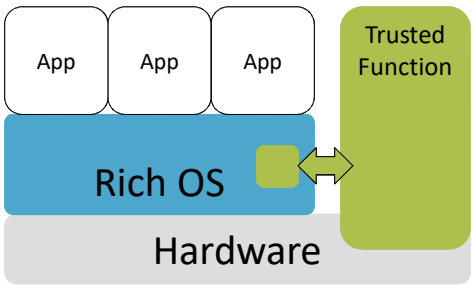
n=6, f=1

	2	3	4	5	6	x(crash)
1 (slow)	2	3	4	5	6 (faulty)	
	2 (faulty)	3	4	5	6	7 (slow)

median validity range

Trusted subsystem

- Assume a part of system cannot go wrong
  - …except for crash faults
  - Enabled by trusted hardware in modern CPUs (ARM TrustZone, Intel SGX)



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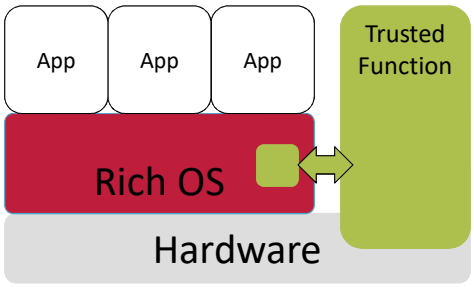
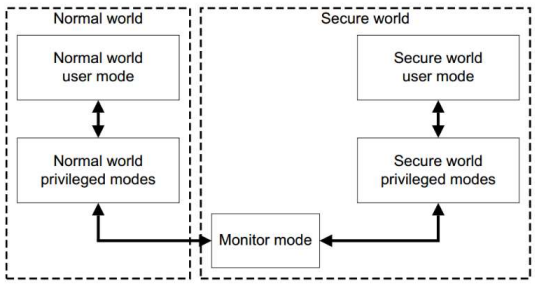


Trusted subsystem: ARM TrustZone

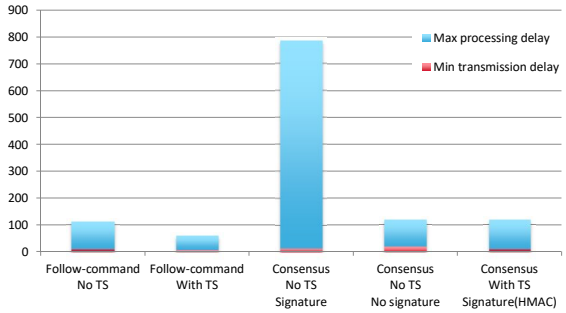
- Tight control of access to secure world (secure monitor call, hardware exceptions)
- Remote attestation: is the function correctly installed on the trusted subsystem?



ARM Security Technology: Building a Secure System using TrustZone Technology, Fig. 3-1

Experiment result

Delay(ms)	Follow-command	Consensus signature-based	Consensus signature-free
No trusted module	113	786	118
With trusted module	60	119 (HMAC)	-



Existing core OS support: Inadequate

- IP multicast just doesn't work...
  - Amazon AWS disables IPMC and tunnels over TCP
- TCP is the main option, but it has some issues:
  - No support for reliable transfer to multiple receivers
  - Uncoordinated model for breaking connections on failure
  - Byte stream model is mismatched to RDMA

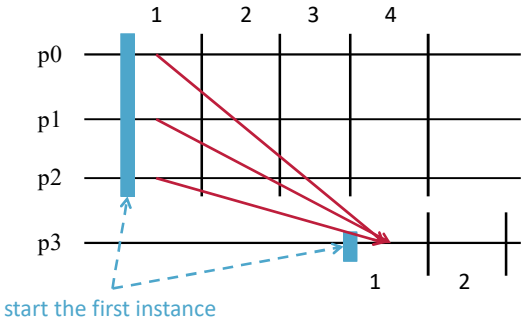
Ken Birman: Evolution of fault tolerance, SOSP History Day 2015

Timing issue

- When periodically agreeing, how to know a message belongs to the current period?
  - Replay attack; Delay attack;
- Timestampped message
  - Reasonable in vehicular communication
  - But not favorable by all people

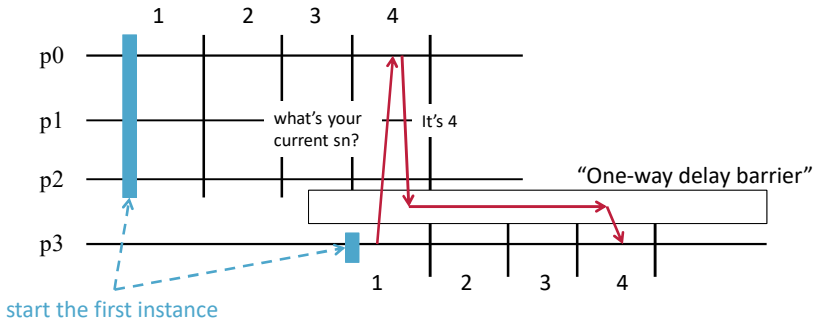
Timing issue

- Sequence number? How to determine the first period?



Timing issue

- Sequence number? How to determine the first period?
- Ask the others for a calibration?



Difference with State Machine Replication

- Limited computation resource & energy
- Communication
  - TCP/IP not suitable. New network stack support needed
  - Broadcast support
  - Network issue, handled in which layer?
- Not require high throughput. Latency more important
- ~~Checkpoint~~, ~~Ordered execution~~

Byzantine fault tolerance

- Synchronous vs asynchronous system model:
  - Synchronous system: message transmission and processing delay has a known upper bound. ➔can detect crashed node

  - Asynchronous system: no upper bound of delay

Difference with State Machine Replication: Philosophy

- SMR:
  - Require fault tolerance -> Replication -> Agreement
  - Agreement serves for fault tolerance, so itself must be FT
  - Can inherit the fault model
- Cooperative system
  - Agreement is an intrinsic service
  - Safety requirement, fault model reasonable?
  - ➢ Maybe that's why convergence approaches dominate?