TinyBFT: Byzantine Fault-Tolerant Replication for Highly Resource-Constrained Embedded Systems

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(Watwa)

BFT Replication Systems Are Getting Smaller

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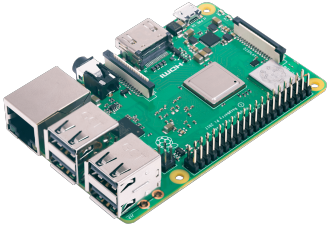
$\gg$32 GB RAM



$\sim$4 GB RAM

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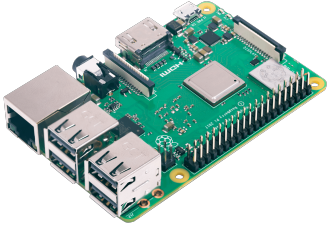
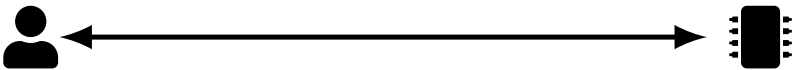


$\sim$4 GB RAM

< 1 MB RAM

Replication



Replication

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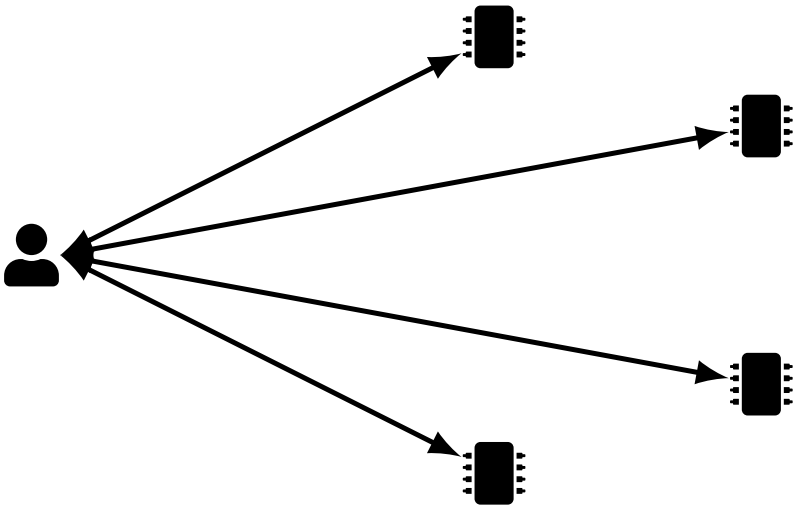

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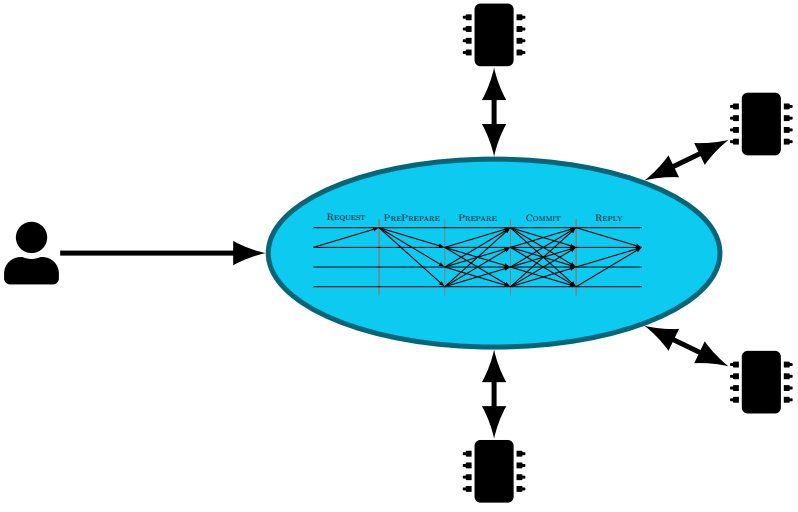
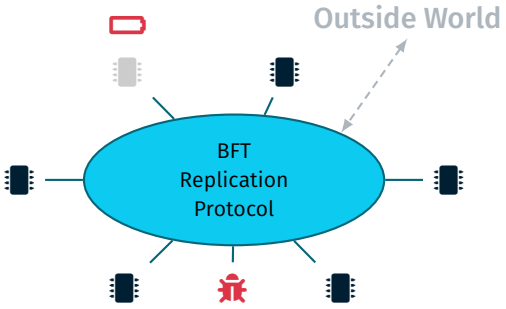


System Model and Fault Model

System Model

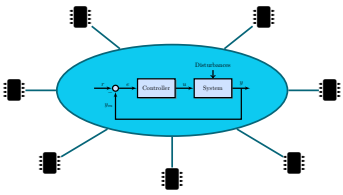
- Limited RAM **(< 1MB)**
- Limited energy
- Wireless communication
- Response times up to a few sec



Fault Model

- Crashes
- Byzantine faults
- $n \geq 3f + 1$

Why do we bother?



1. Resilient control applications [3]
2. Blockchain-based data recording
3. Eco-friendly room booking

Existing Replication Software Is Not Ready For These Systems

- Implementations target *server-grade* hardware
- Use of large runtime environments (e.g., JRE)
- **Memory plays (almost) no role in design**

< 1 MB RAM

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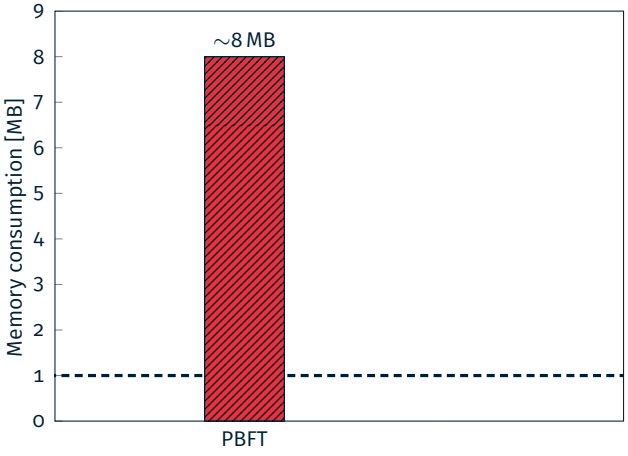

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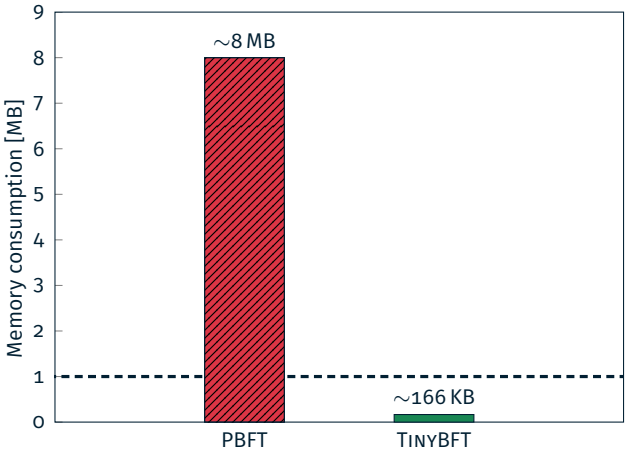

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Small Devices, Unique Challenges

Three key challenges running BFT replication in target environment:

Challenge 1

Selecting the right protocol design

Challenge 2

Reducing protocol's memory footprint

Challenge 3

Exploiting additional (non-volatile) memory modules

Small Devices, Unique Challenges

Three key challenges running BFT replication in target environment:

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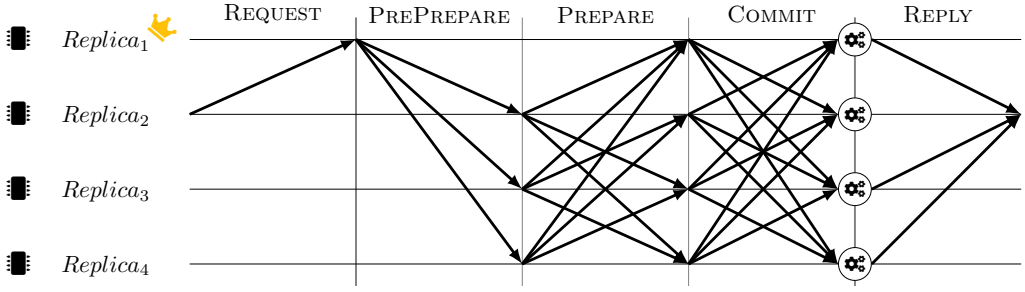
Carefully selected PBFT as best fit for our use-case

Challenge 2

Reducing protocol's memory footprint

Challenge 3

Exploiting additional (non-volatile) memory modules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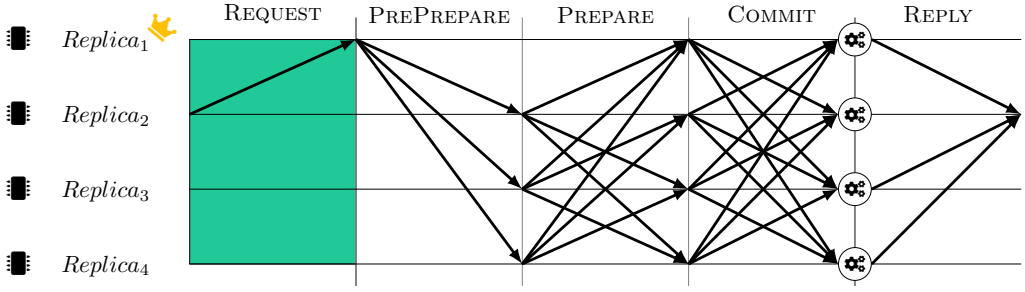
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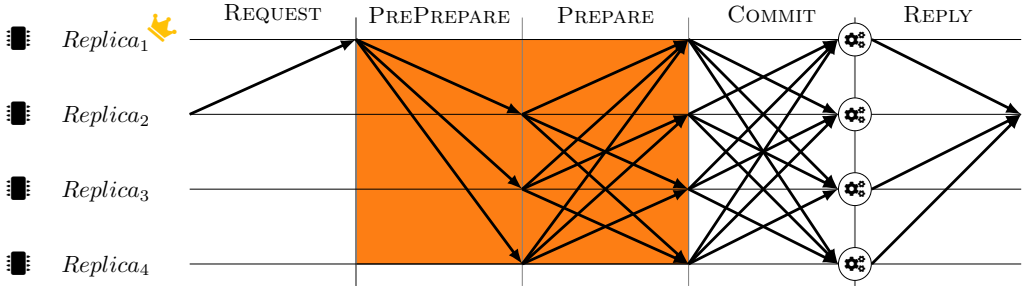
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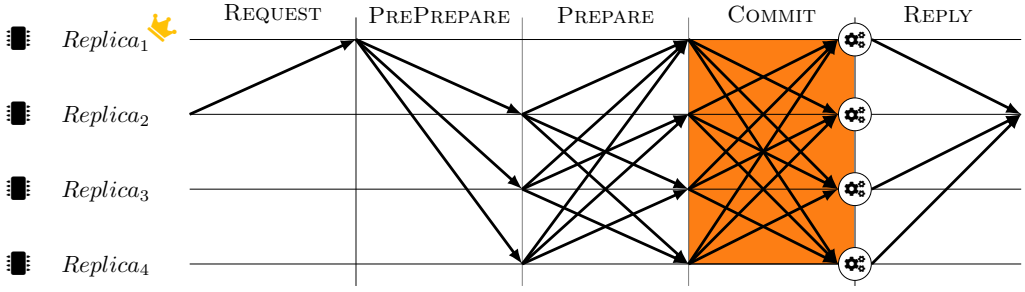
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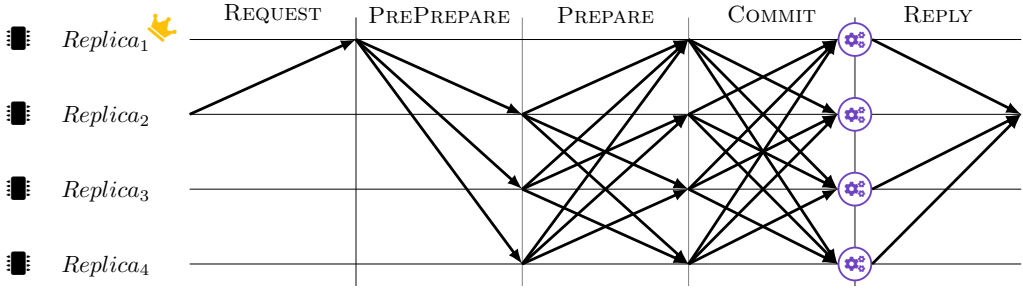
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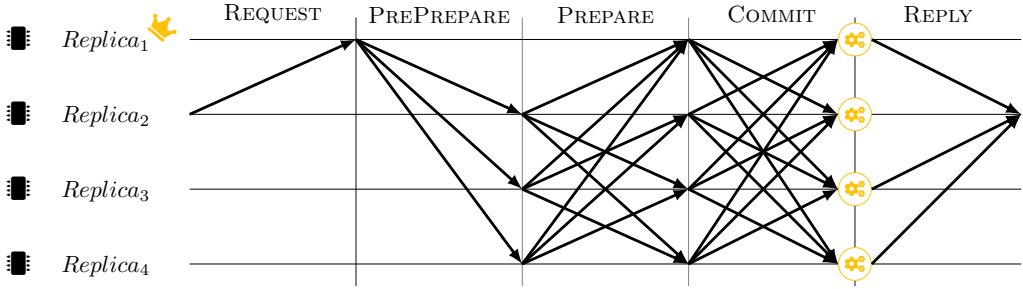
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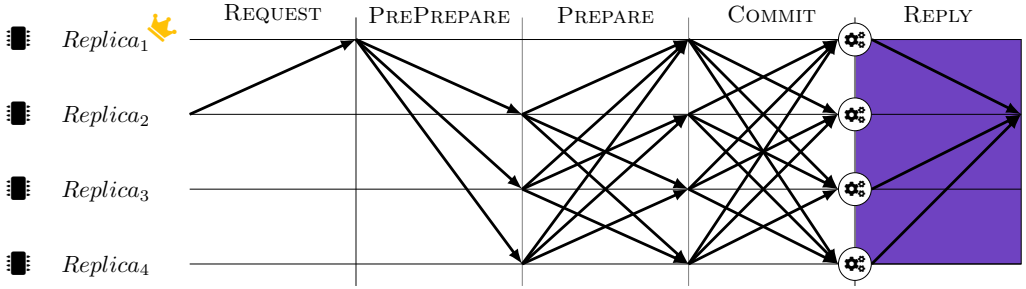
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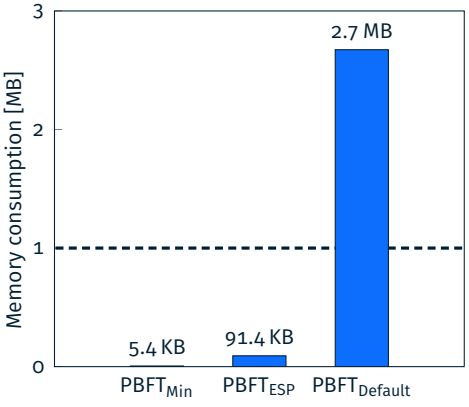
- Theoretical memory demand
- Assess demand of configurations
- Baseline for implementations



TinyBFT: Optimizations


Scratch
Agreement
Checkpoint
Event


Scratch
Agreement
Checkpoint
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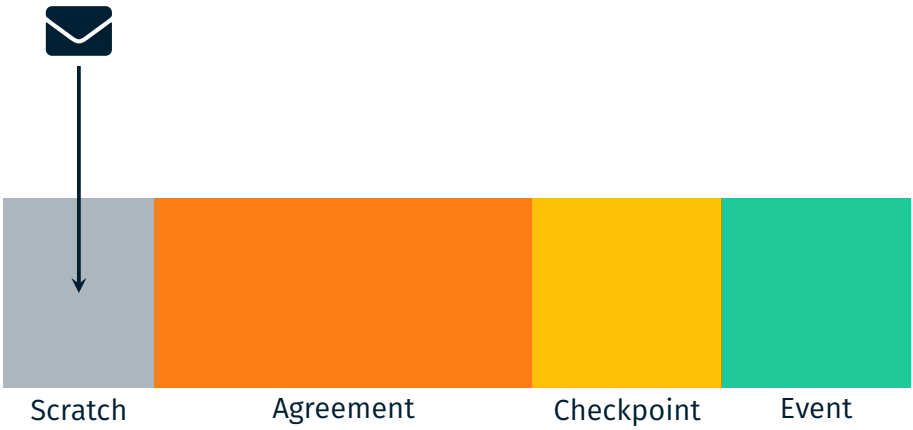
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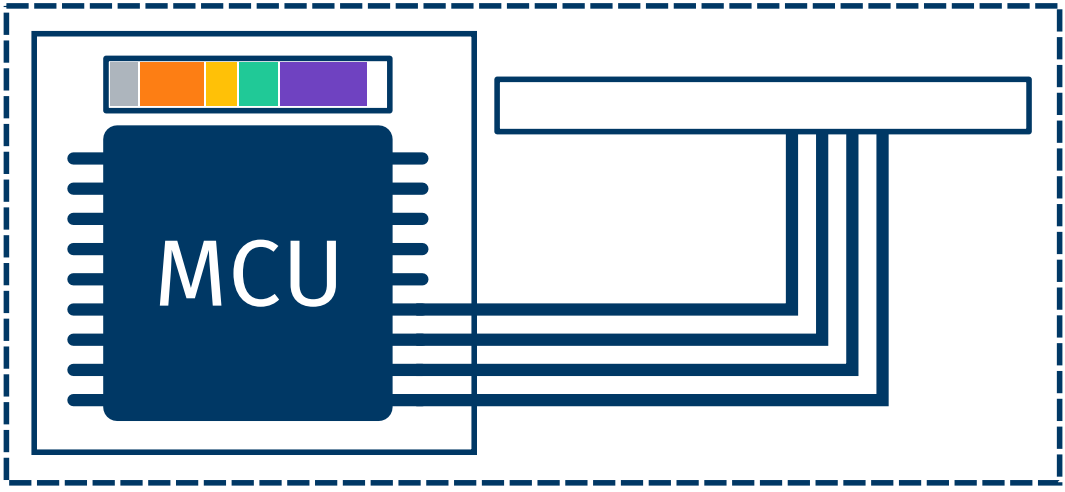
MCU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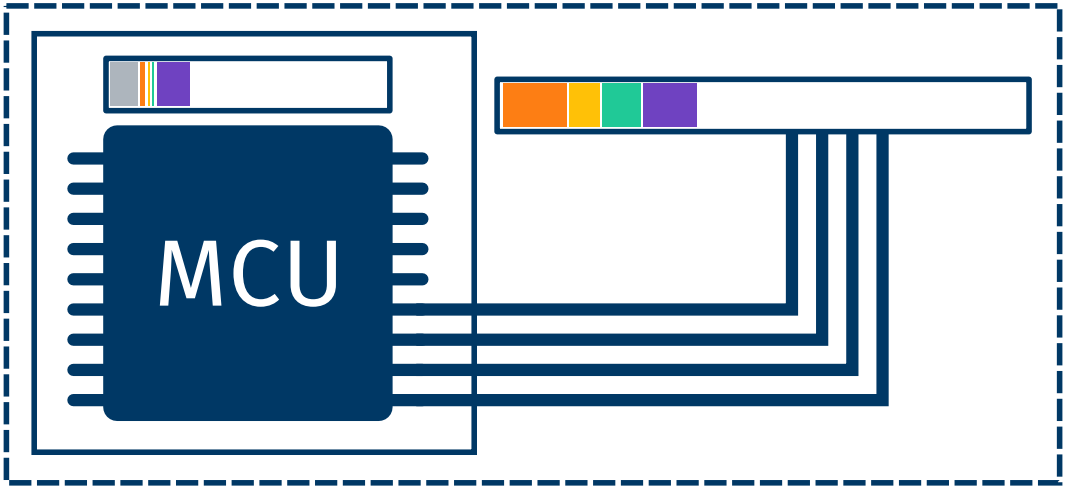
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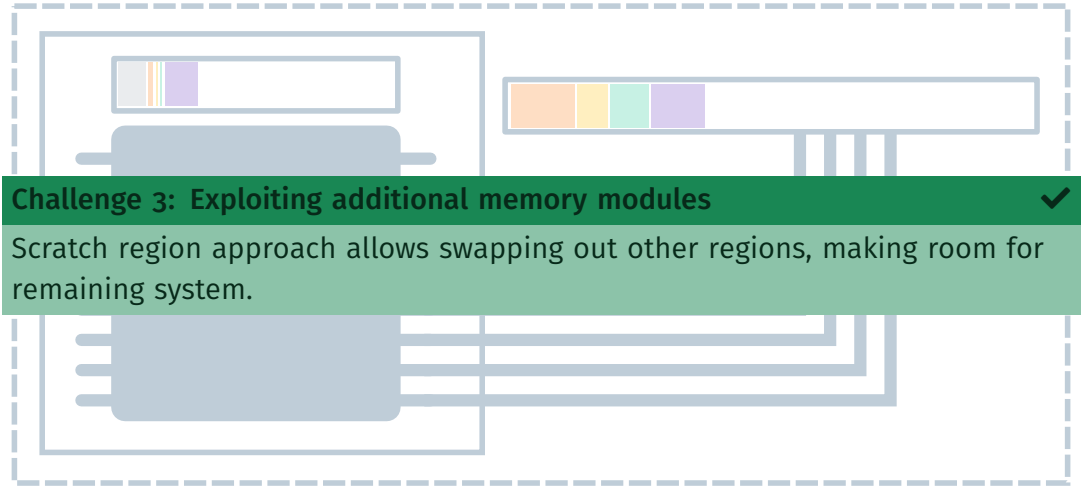
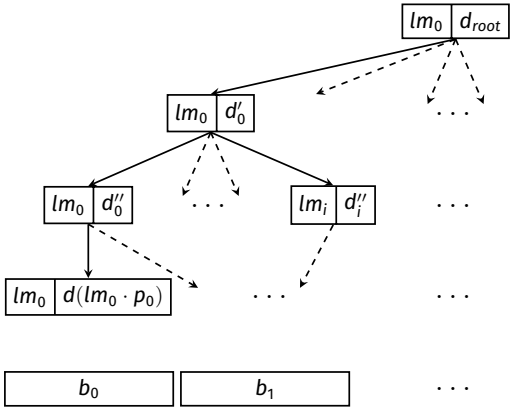


Challenge 3: Exploiting additional memory modules ✓

Scratch region approach allows swapping out other regions, making room for remaining system.

- State divided into blocks
- Tree structure to track changes
- Enables efficient state transfer
- PBFT's tree is fixed size
- TinyBFT's tree adjusted to state size



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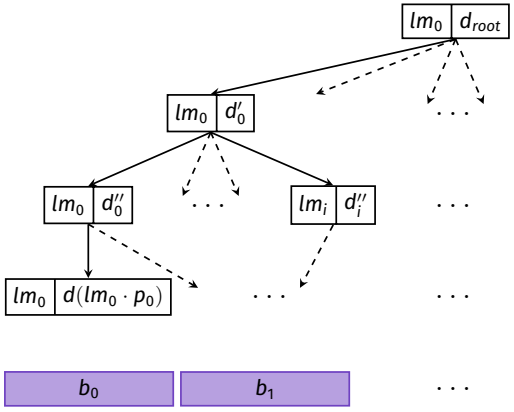

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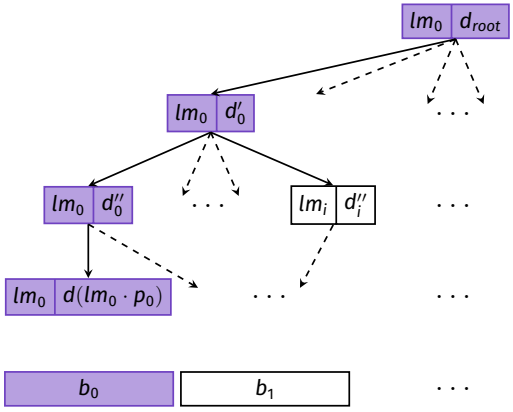

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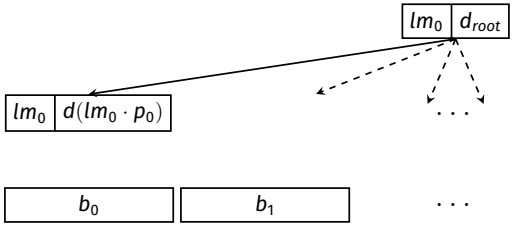
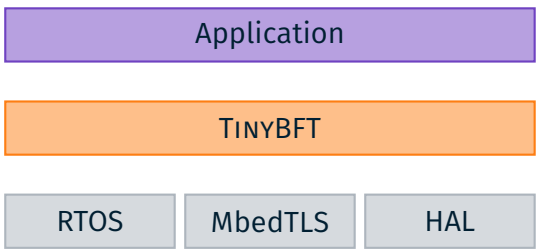


- Flexible configuration mechanism
- Tailor protocol to specific needs
- Sanity checks during compile time

- Based on PBFT prototype [1, 2]
- MBedTLS for Cryptography
- HAL for hardware timers



Evaluation

Protocol Part	PBFT (Intel)	TinyBFT (ESP32-C3)	Regions
Client handling	5,952 B	11,460 B	
Agreement	1,320 B	11,908 B	
Execution	7,395,588 B	115,780 B	
View	1,992 B	7,920 B	
Other	554,984 B	18,447 B	
Total	**7,959,872 B**	**165,515 B**	

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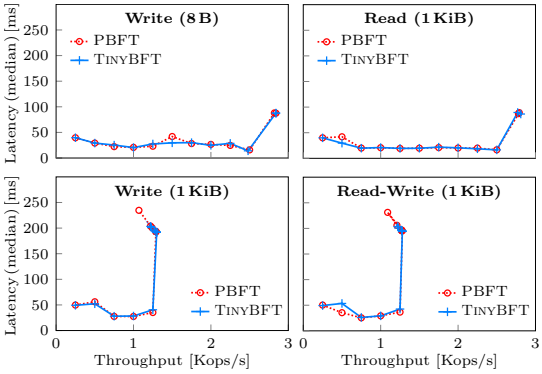
Challenge 2: Reducing PBFT's memory footprint ✓

TinyBFT is able to run on target hardware.

- **Platform:** Intel Xeon (Skylake) (3.6 GHz, 16 GB RAM)
- **Application:** Key-value Store
- $f = 1$



- **Platform:** ESP32-C3 (160 MHz, 400 KB RAM)
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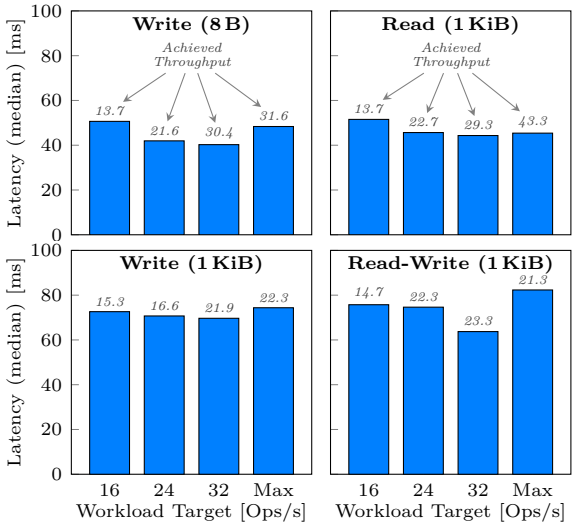

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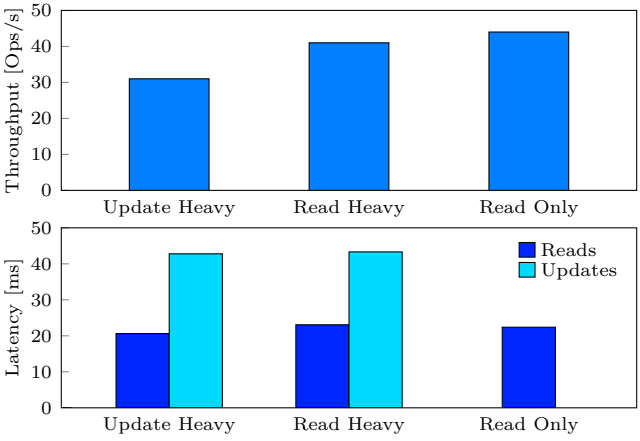
- YCSB Benchmark
- 256 B Records



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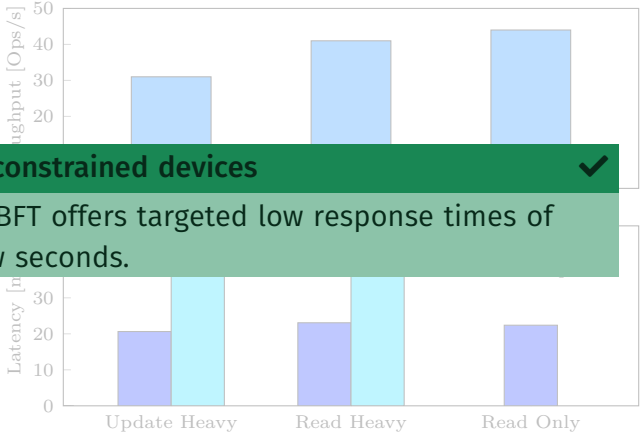

Performance on highly resource-constrained devices ✓

With latencies below 100ms, TinyBFT offers targeted low response times of hundreds of milliseconds to a few seconds.

Conclusion

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Thank you for your attention! Questions?

Source available at: `https://gitos.rrze.fau.de/tinybft`

Appendix

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References (1)


M. Castro and B. Liskov.
Practical Byzantine fault tolerance.
In *Proceedings of the 3rd Symposium on Operating Systems Design and Implementation (OSDI '99)*, pages 173–186, 1999.


M. Castro and B. Liskov.
Practical byzantine fault tolerance and proactive recovery.
ACM Transactions on Computer Systems (TOCS), 20(4):398–461, 2002.


A. Gujarati, N. Yang, and B. B. Brandenburg.
In-ConcReTeS: Interactive consistency meets distributed real-time systems, again!
In *Proceedings of the 43rd Real-Time Systems Symposium (RTSS '22)*, pages 211–224, 2022.

References (2)