Fault-Tolerant Distributed Transactions on Blockchain

Beyond the Design of PBFT



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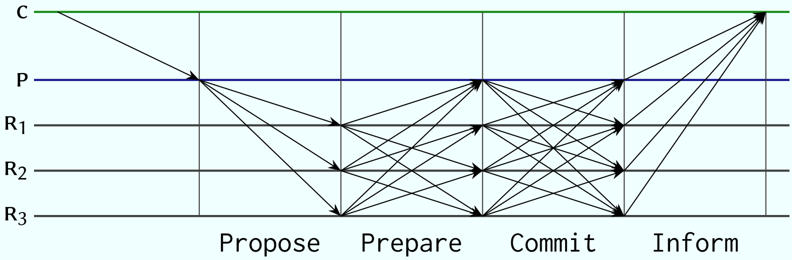
UCDAVIS
UNIVERSITY OF CALIFORNIA

ExpoLab
Creativity Unfolded

McMaster
University

Previously: PBFT



Central Question

What is the *expected performance* of PBFT? Motivate!

On the Performance of Consensus

Consensus throughput	Decisions per second made by consensus.
Consensus latency	Duration of a single round of consensus.
Resource utilization	The cost of consensus (e.g., computational, network bandwidth). *Imbalance* in resource utilized by replicas (e.g., primary).

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Client latency	Duration between a client request and the outcome. ▶ *Low loads*: Function of the consensus latency. ▶ *High loads*: Function of the consensus throughput.

Determining the Performance Variables

Number of replicas	determines the amount of messages exchanged.
Network bandwidth	determines how long it takes to exchange these messages.
Message delay	determines how long it takes for sent messages to arrive.
Computational speed	determines the speed by which messages are processed.

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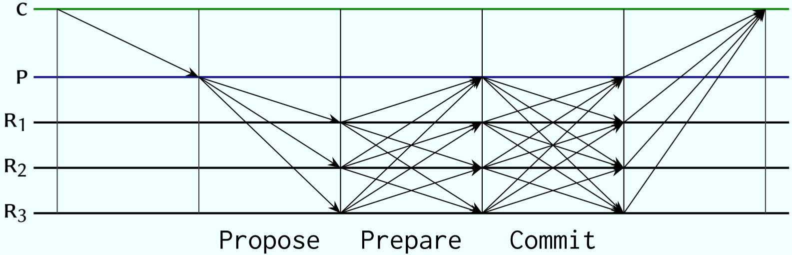
Bottleneck in practice: consensus performance in terms of throughput and latency (as a function of *network bandwidth* and *message delay*).

The Single-Round Cost of PBFT (Sketch)

Assumption: Network bandwidth $B = 100\,\mathrm{MiB/s}$ and delay $\delta = 15\,\mathrm{ms}$



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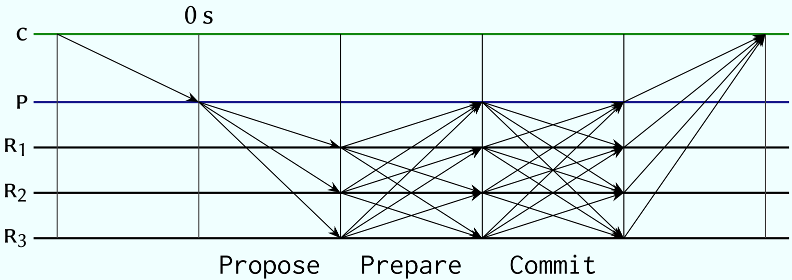

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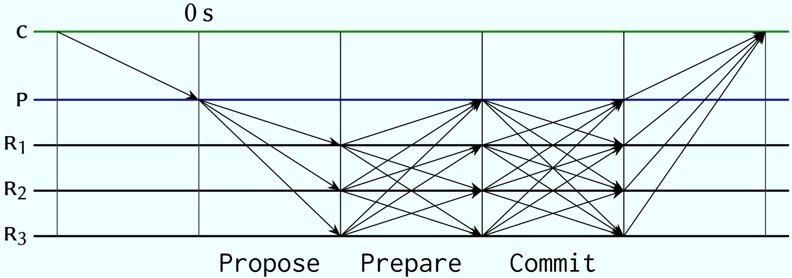

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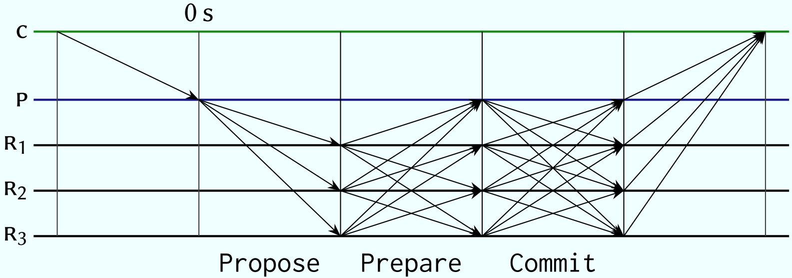

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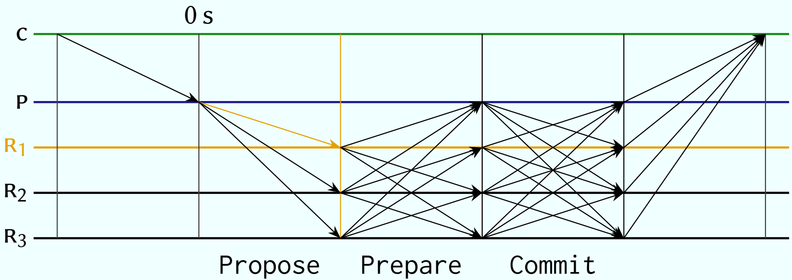

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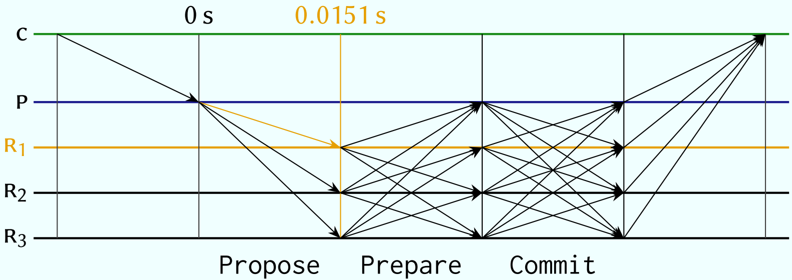

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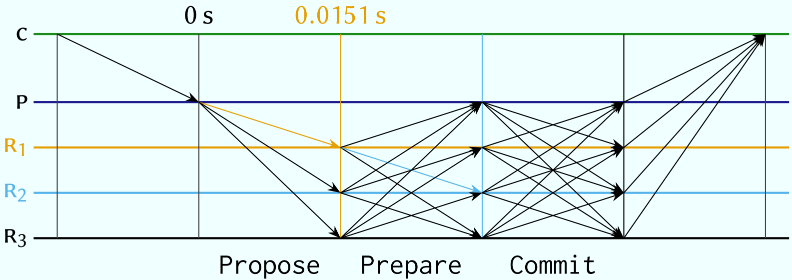

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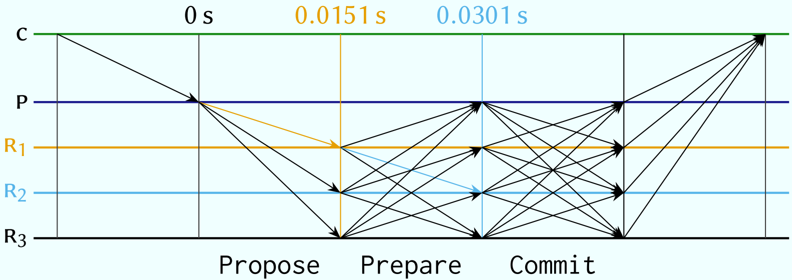

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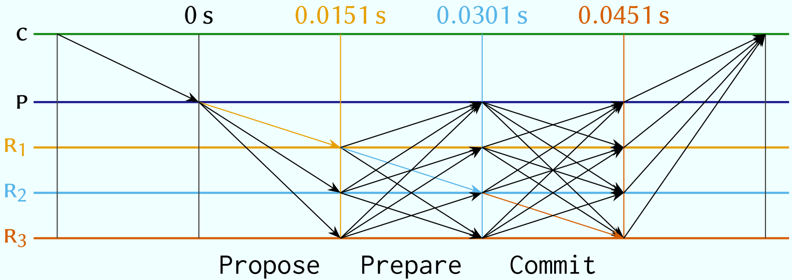

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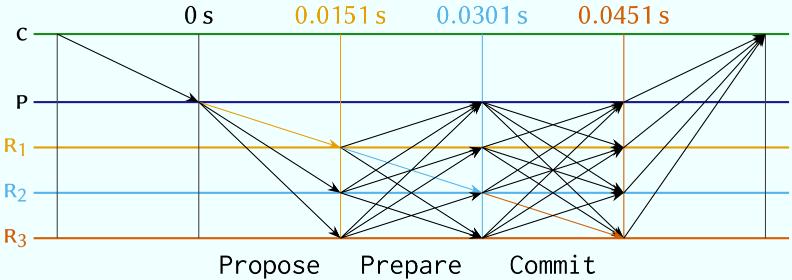

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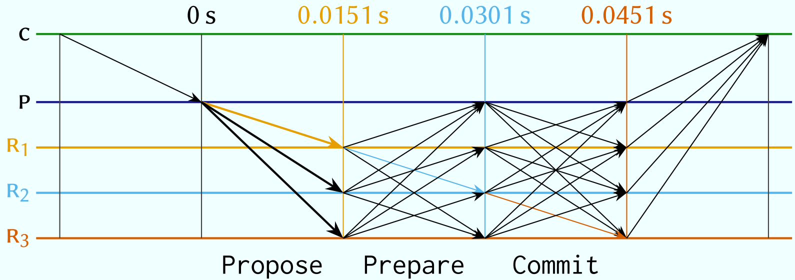

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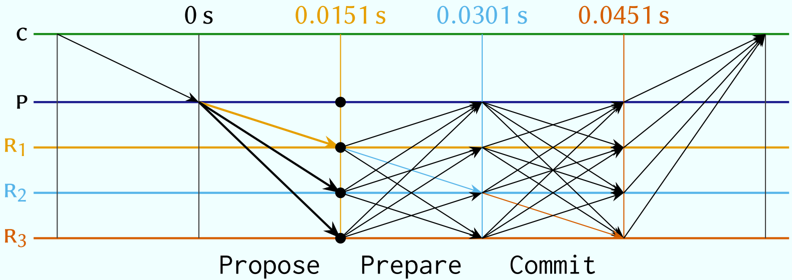

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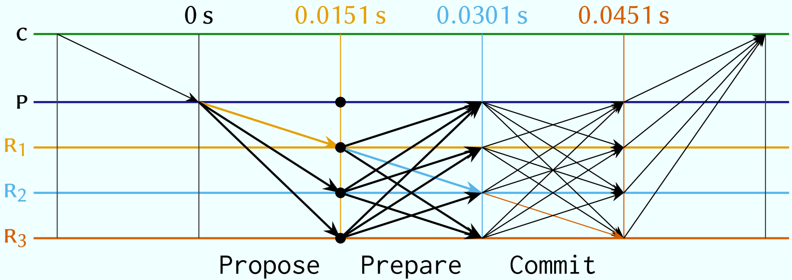

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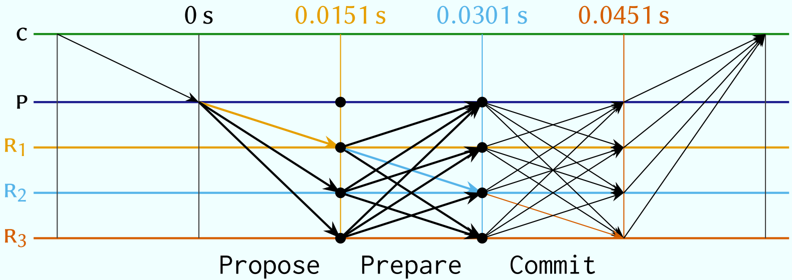

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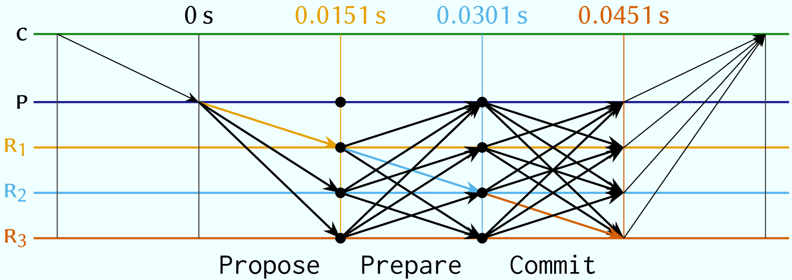

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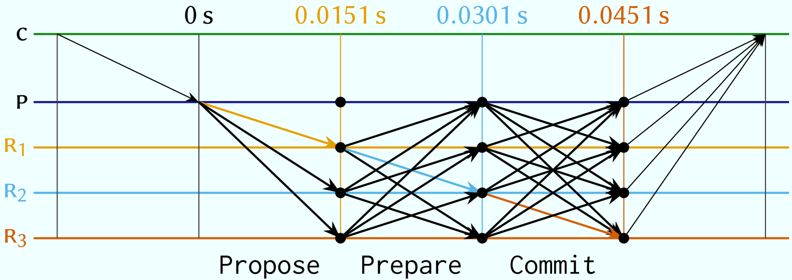

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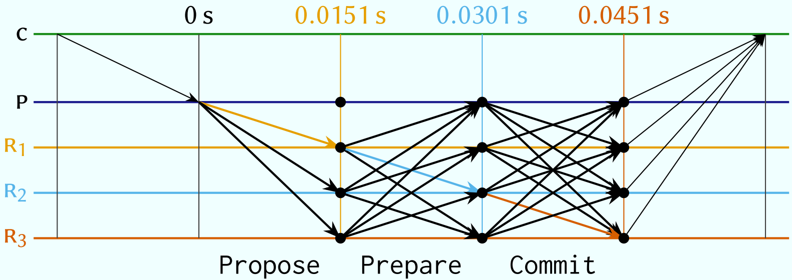

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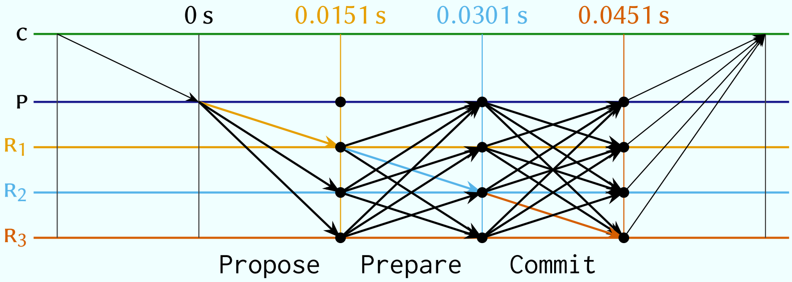

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$\approx 3\delta$ (assuming *high delay relative to bandwidth*).

The Throughput of PBFT

Sequential: Next consensus round starts after finishing the current round

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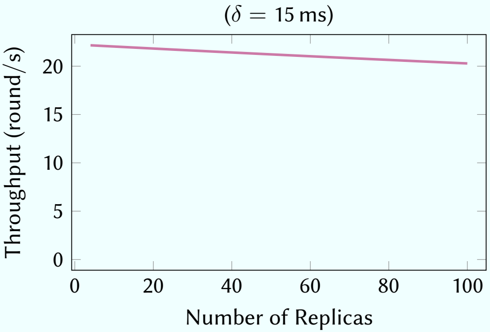

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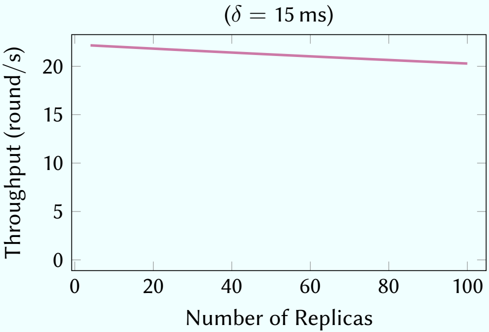

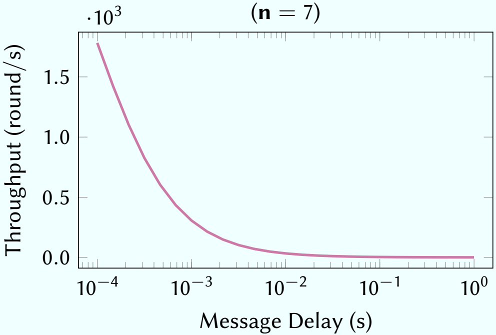

Implementation techniques for PBFT

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Fine-tuning PBFT implementations

Batching	many transactions per consensus decision.
Out-of-order processing	many consensus decisions at the same time.
Overlapping	phases of consecutive rounds.

Batching Client Requests

The cost of a single round of PBFT

Message	Sent by	Size
`Propose`	Primary	s_{t}
`Prepare`	Backups	s_{m}
`Commit`	All	s_{m}

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Batching: each decision is on **m** transactions.

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`Commit`	All	s_m	s_m
Total:	$2\mathbf{n}(\mathbf{n}-1)$	$\mathcal{O}(s_t\mathbf{n} + s_m\mathbf{n}^2)$	$\mathcal{O}(ms_t\mathbf{n} + s_m\mathbf{n}^2)$

The Throughput of PBFT with Batching

Sequential, batching *m* transactions per consensus round

$$\Delta_{\text{PBFT-}m} = \frac{m(\mathbf{n}-1)s_{\mathrm{t}} + 2(\mathbf{n}-1)s_{\mathrm{m}}}{B} + 3\delta;$$

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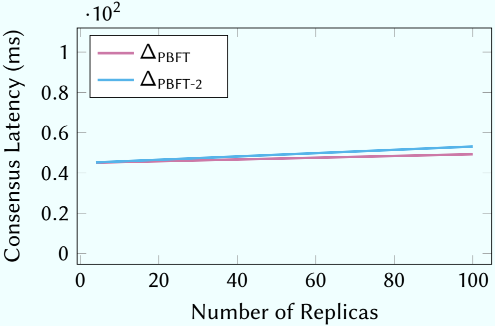

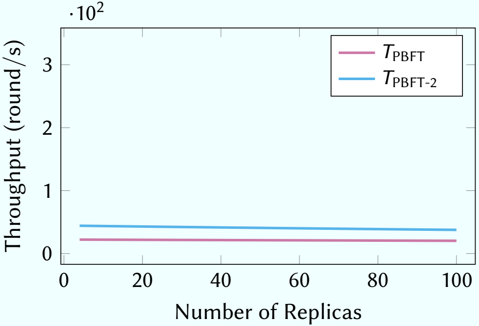

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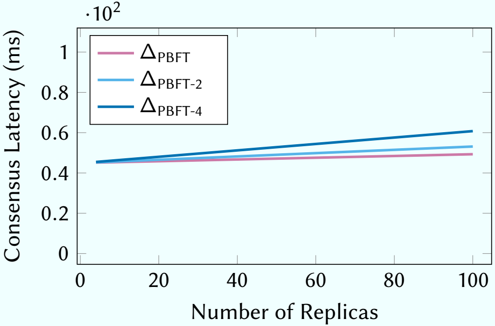

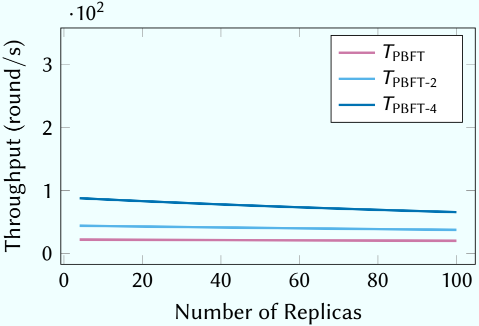

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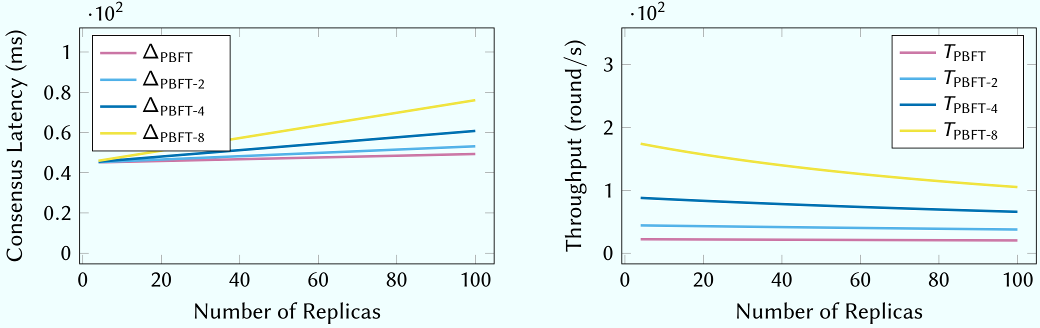

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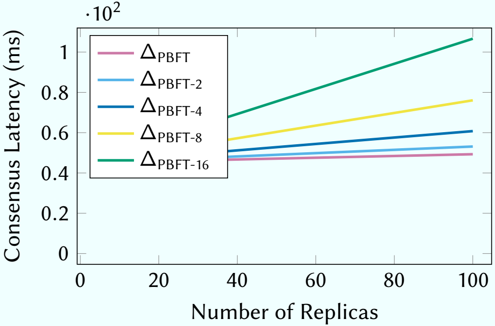

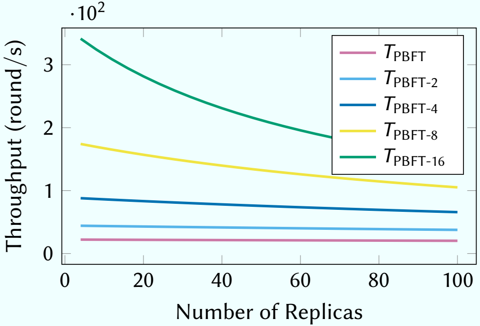

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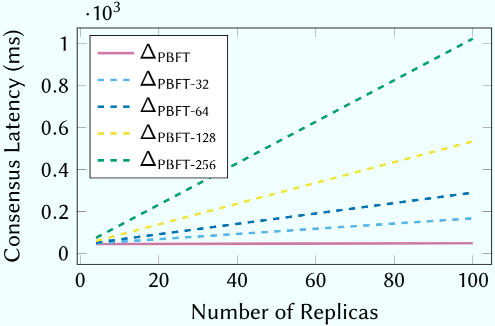

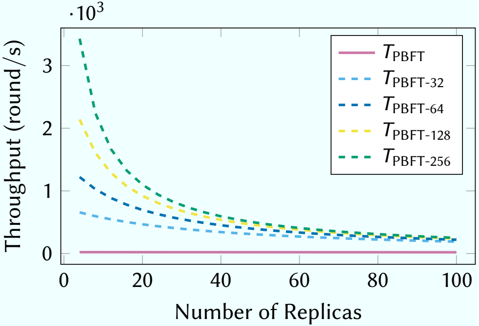

Using Batching to Improve Throughput Scalability

	Messages	*(per trans.)*	Size	*(per trans.)*
PBFT	$2\mathbf{n}(\mathbf{n}-1)$	$2\mathbf{n}(\mathbf{n}-1)$	$\mathcal{O}(s_{\mathrm{t}}\mathbf{n} + s_{\mathrm{m}}\mathbf{n}^2)$	$\mathcal{O}(s_{\mathrm{t}}\mathbf{n} + s_{\mathrm{m}}\mathbf{n}^2)$

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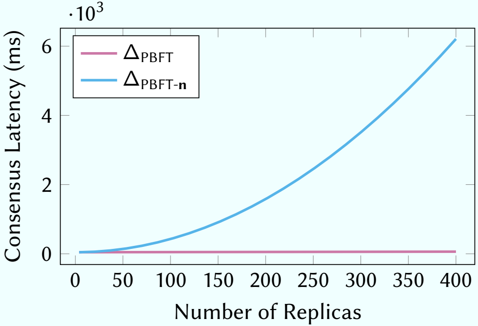

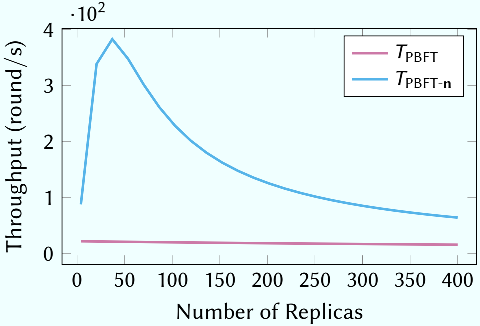

Resource Utilization of Sequential PBFT

Assumption: $\mathbf{n} = 4$, $B = 100\,\text{MiB/s}$, $\delta = 15\,\text{ms}$, $s_{\mathrm{t}} = 4048\,\text{B}$, $s_{\mathrm{m}} = 256\,\text{B}$

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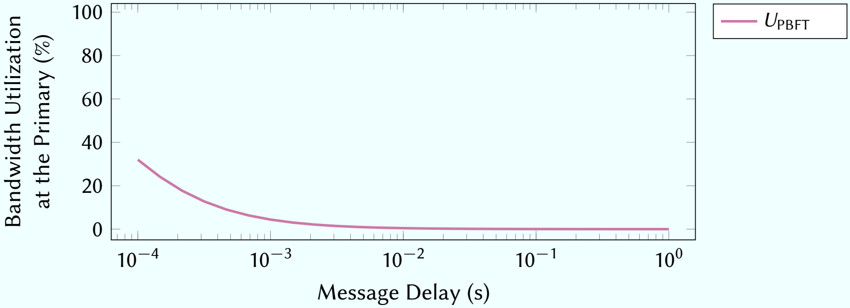

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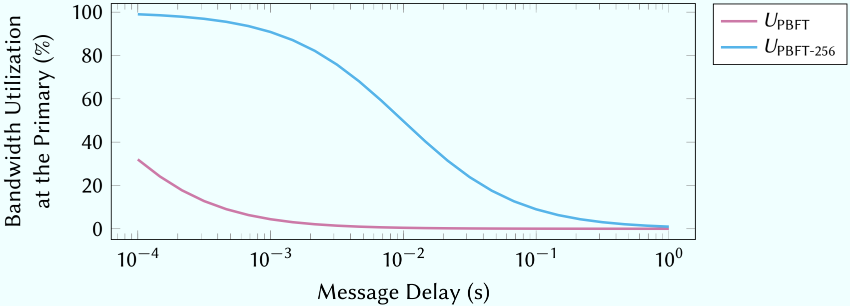

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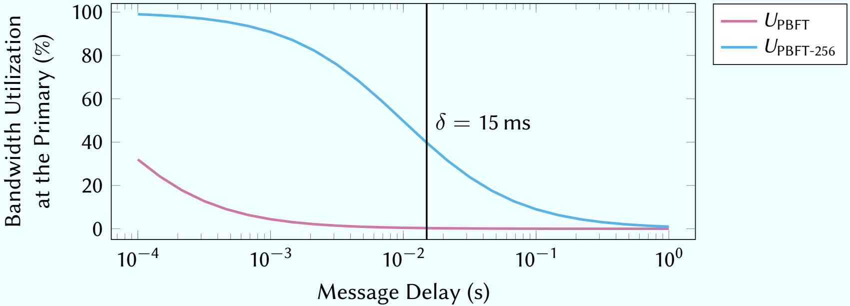

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Limit proposals to an *active window* of valid rounds.
E.g., only proposals in 1000 rounds after the last finished round.

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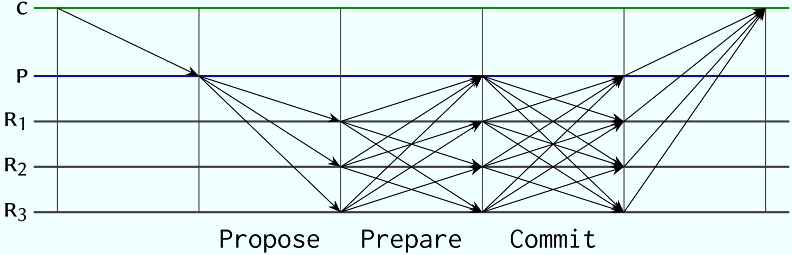
Assumption: Primary does most work ($s_t > s_m$)



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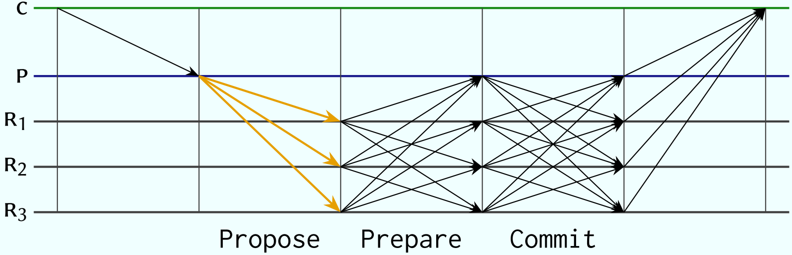

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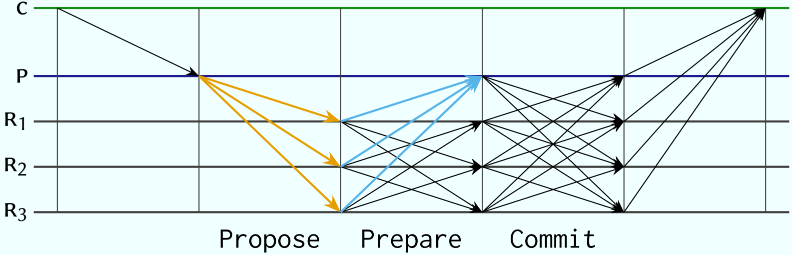

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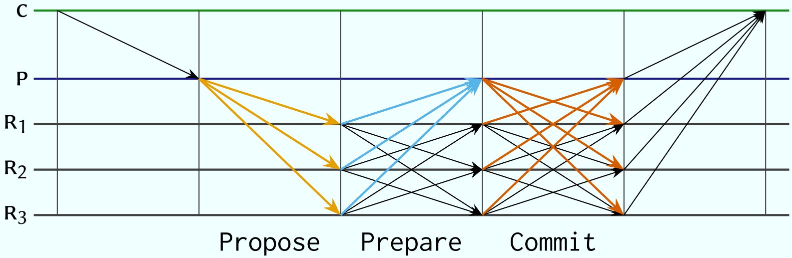

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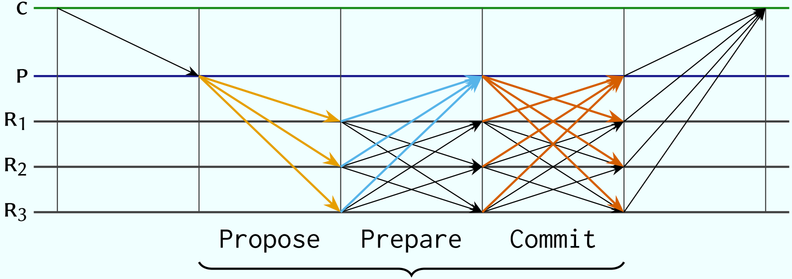

$$\underbrace{(\mathbf{n}-1)s_t + (\mathbf{n}-1)s_m + 2(\mathbf{n}-1)s_m}_{} = (\mathbf{n}-1)(s_t + 3s_m)\ \mathrm{B/round.}$$

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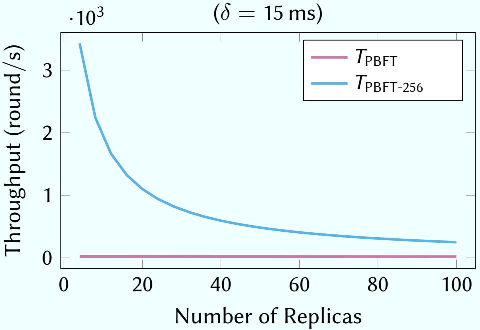

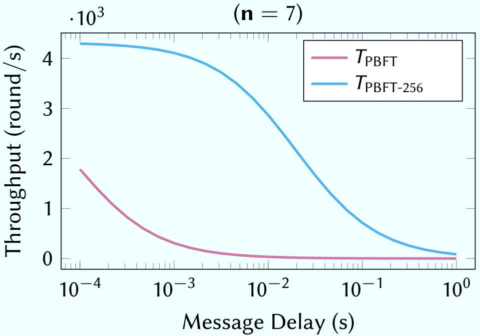

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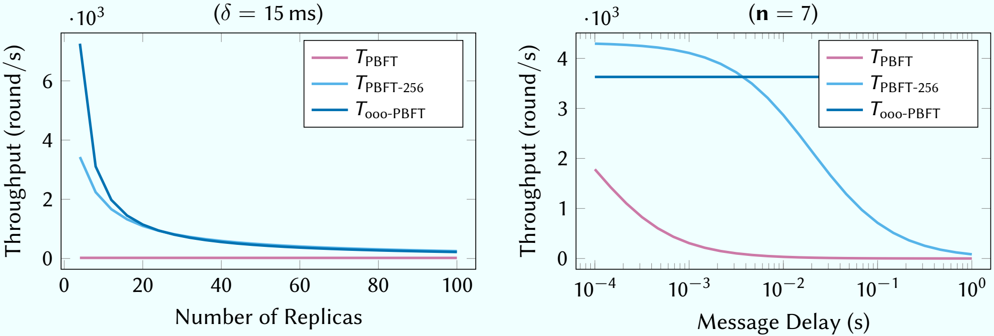

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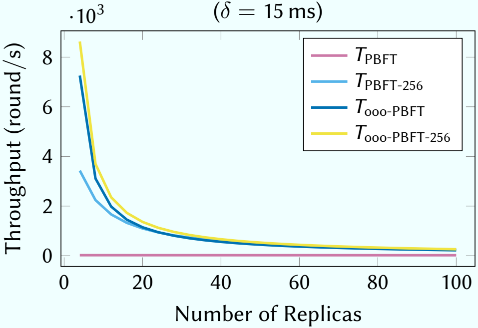

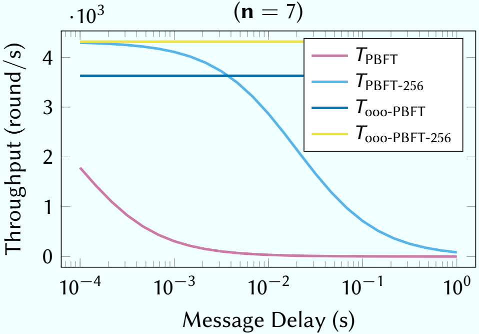

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Implies strict consecutive processing of rounds

Overlapping *cannot* be combined with out-of-order processing!

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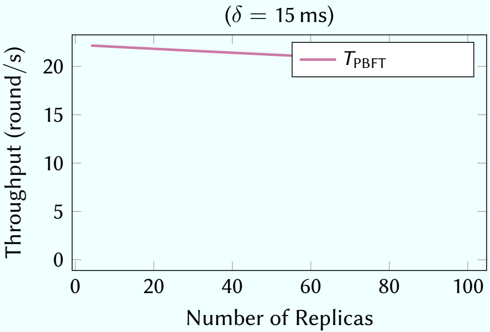

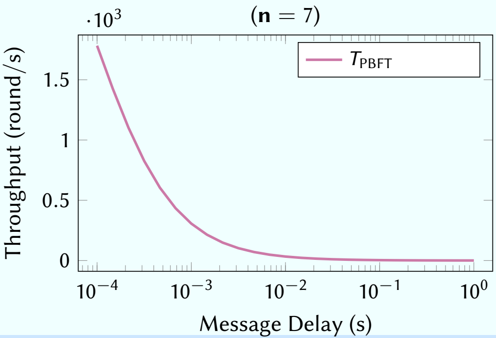

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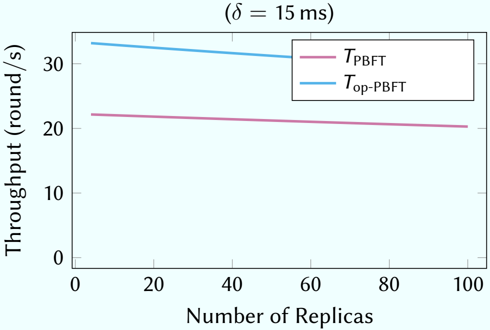

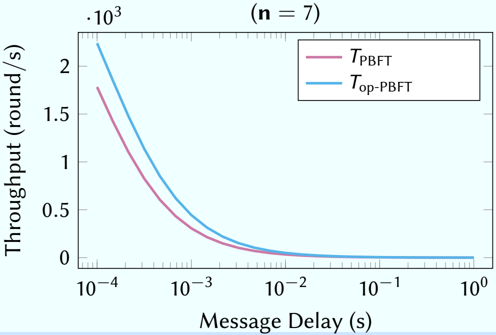

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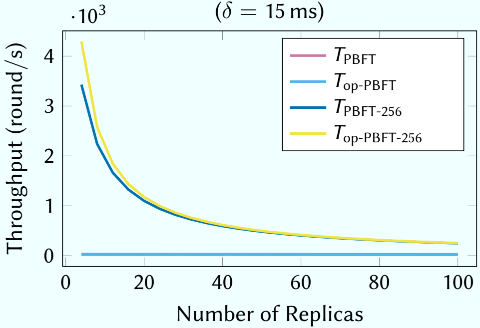

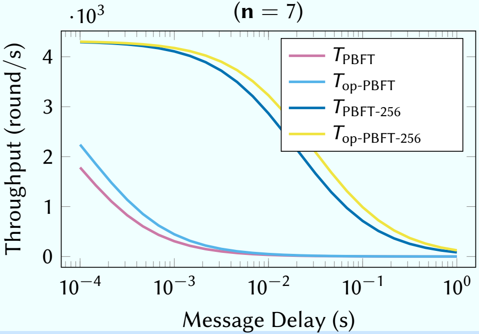

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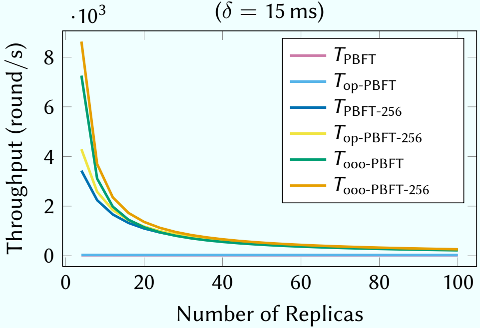

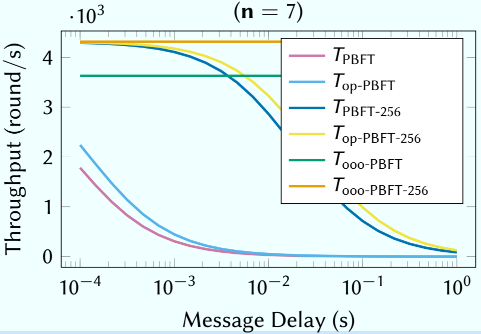

Implementation techniques for PBFT: Summary

Batching	introduces very high round latencies.
Out-of-order processing	has high implementation complexity.
Overlapping	only provides limited gains.

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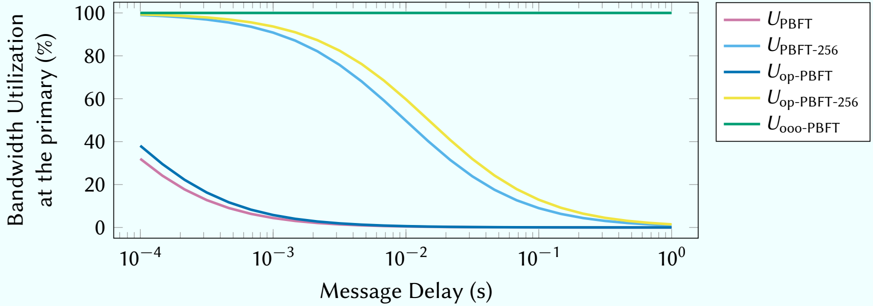

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A PBFT-like design is at the basis of *many* consensus protocols.

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Technologies employed by PBFT-like consensus

Threshold signatures eliminate quadratic all-to-all communication.

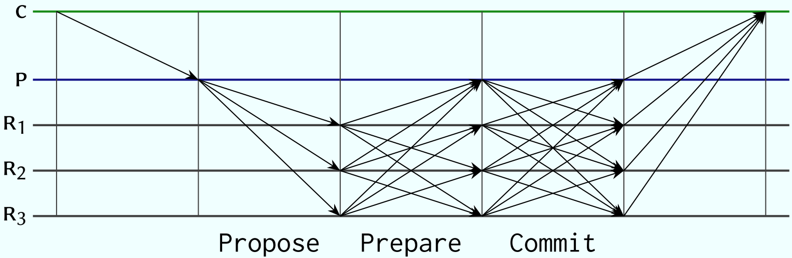
Speculative execution execute before strong recovery guarantees are met.

Optimistic execution fully optimize for when the primary is correct.

Trusted components use hardware components that cannot behave Byzantine.

Here, we will only cover *threshold signatures*.

All-to-All Communication in PBFT



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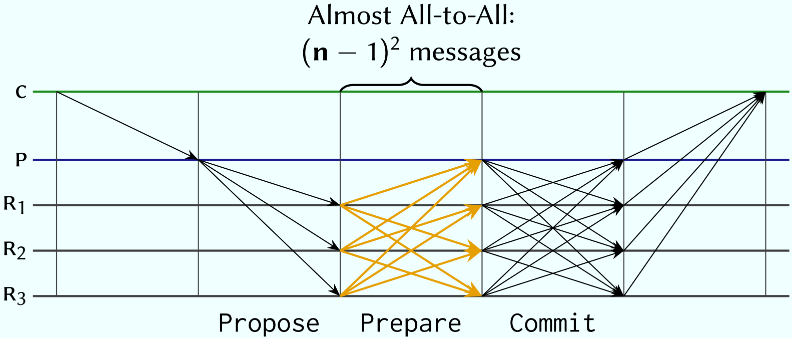

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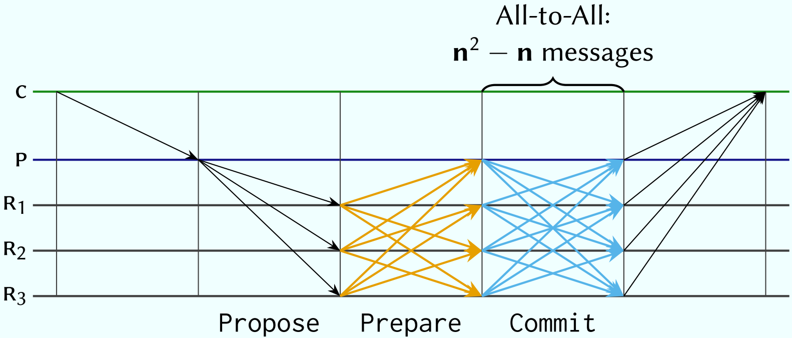

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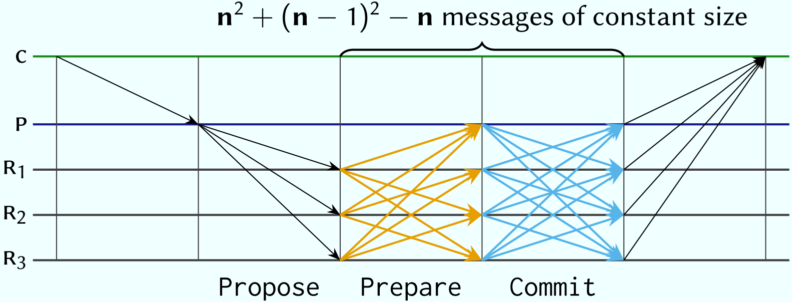

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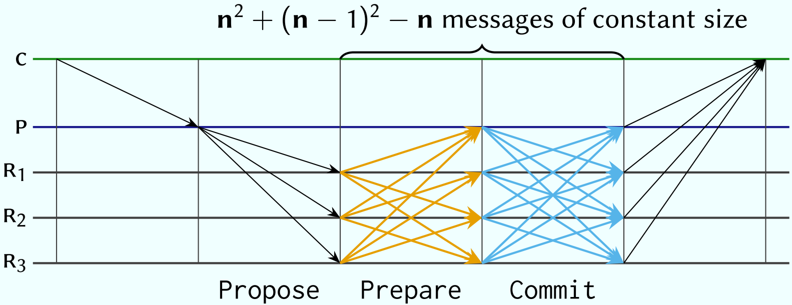
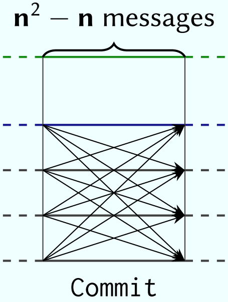


Challenge: Reduce communication from $\mathcal{O}(\mathbf{n}^2)$ to $\mathcal{O}(\mathbf{n})$ *messages of constant size*.

Tackling All-to-All via All-to-one-to-All Aggregation

Consider the commit phase



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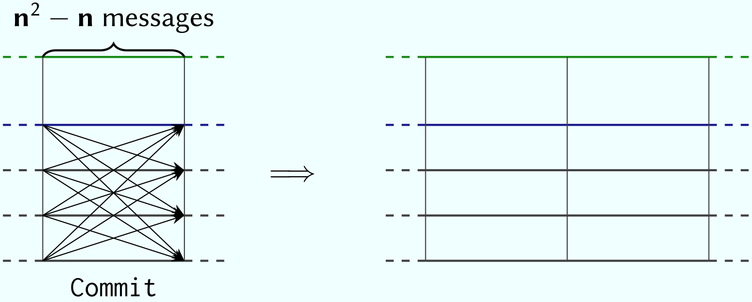

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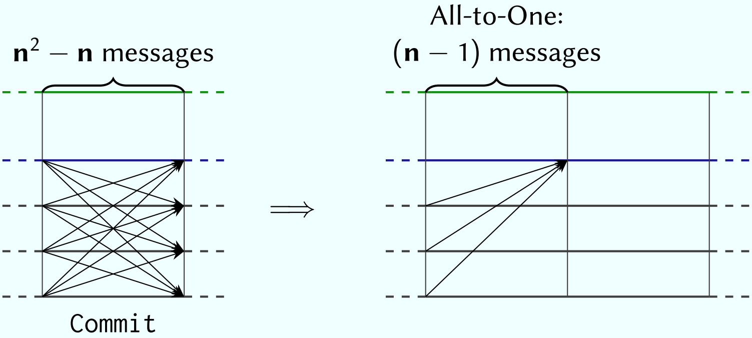

Idea: All replicas send to *one aggregator* that then sends to all replicas.

1. All replicas send their `Commit` messages to the aggregator.

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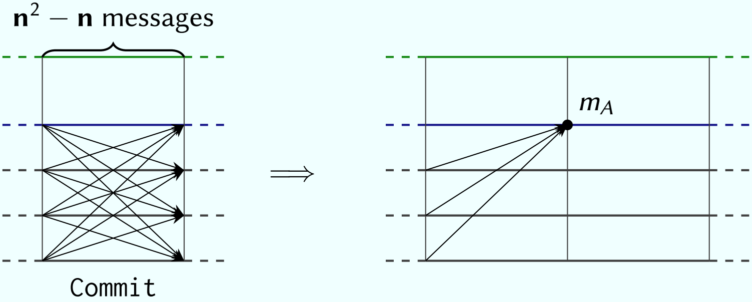

Idea: All replicas send to *one aggregator* that then sends to all replicas.

2. The aggregator combines $\mathbf{n} - \mathbf{f}$ `Commit` messages into an aggregated message m_A.

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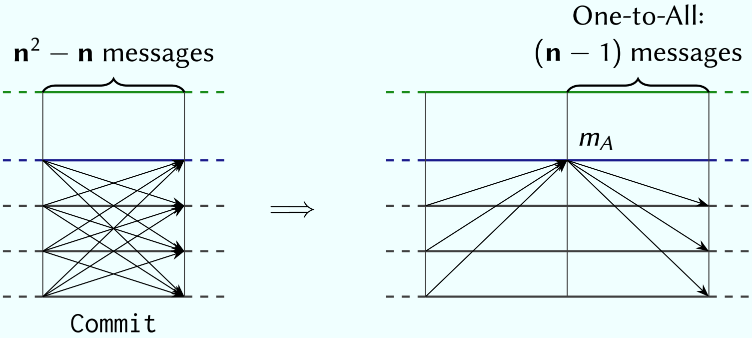

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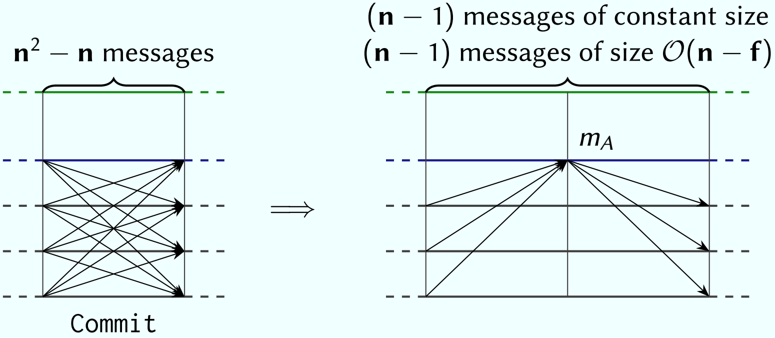

Idea: All replicas send to *one aggregator* that then sends to all replicas.

3. The aggregator sends m_A to all replicas *of size* $\mathcal{O}(\mathbf{n}-\mathbf{f})$ *each*.

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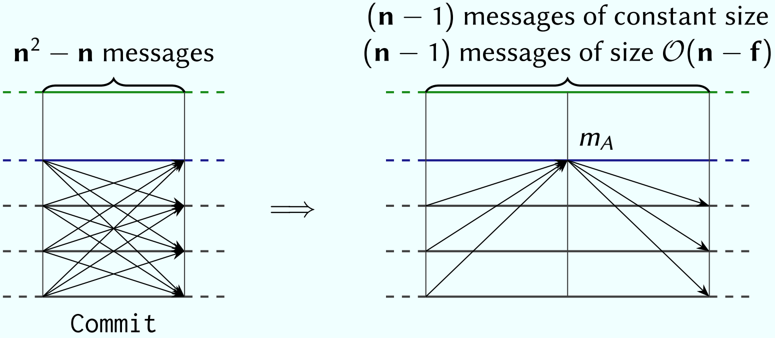

Idea: All replicas send to *one aggregator* that then sends to all replicas.

Effectively reduced communication from $\mathcal{O}(\mathbf{n}^2)$ to $\mathcal{O}(\mathbf{n}(\mathbf{n} - \mathbf{f}))$.

Improving Aggregation with Threshold Signatures

Problem: An aggregated message of size c will have size $\mathcal{O}(c(\mathbf{n}-\mathbf{f}))$.

- We have identical `Commit` messages from at-least $\mathbf{n}-\mathbf{f}$ replicas.
- Goal: aggregate these into a single message of size $\mathcal{O}(c)$ instead of $\mathcal{O}(c(\mathbf{n}-\mathbf{f}))$.

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Solution: Using a $\mathbf{n} : \mathbf{f}$-threshold-signature scheme with public key K

- Each replica has a unique private key.
- Replicas can produce partial signatures for value v using their private key.
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Threshold signatures aggregate $\mathbf{n} - \mathbf{f}$ distinct signatures into a *single constant-sized* value.

All-to-one-to-All Aggregation with Threshold Signatures

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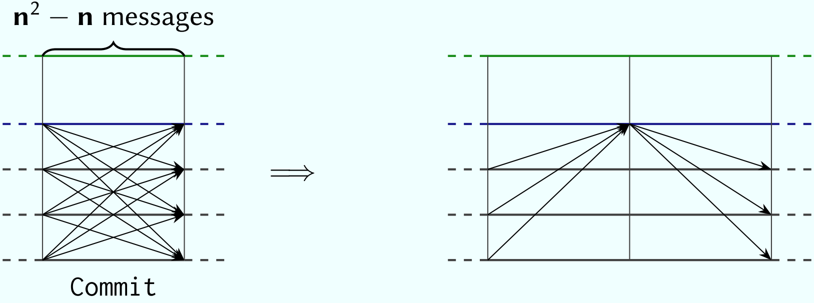

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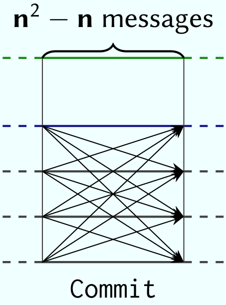

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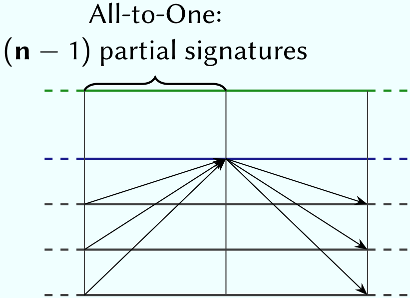

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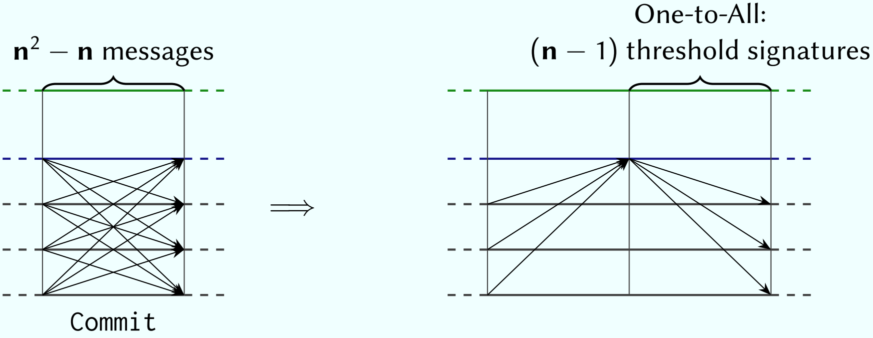

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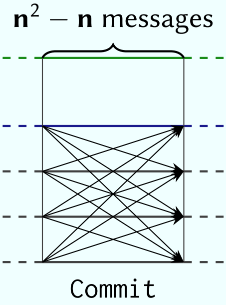

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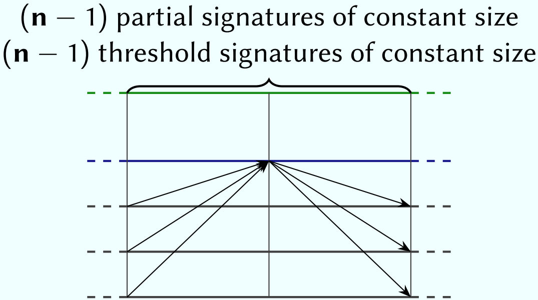

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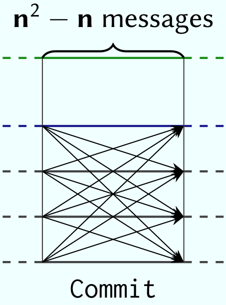

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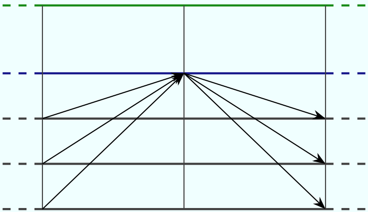

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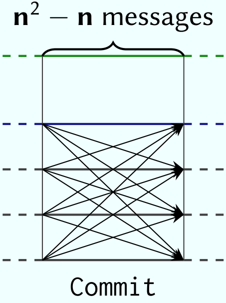

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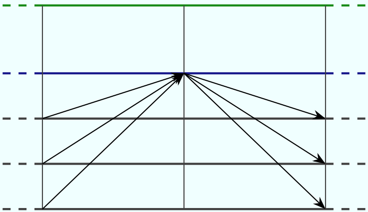

Effectively reduced communication from $\mathcal{O}(\mathbf{n}^2)$ to $\mathcal{O}(\mathbf{n})$.
Similar change can be made to the prepare phase.

Using Threshold Signatures in PBFT

- Both prepare and commit phase: from $2(\mathbf{n}-1)^2$ to $4(\mathbf{n}-1)$ messages.
- Consensus from *three* to *five* rounds: higher consensus and client latencies.
- High *computational cost* for the aggregrator.
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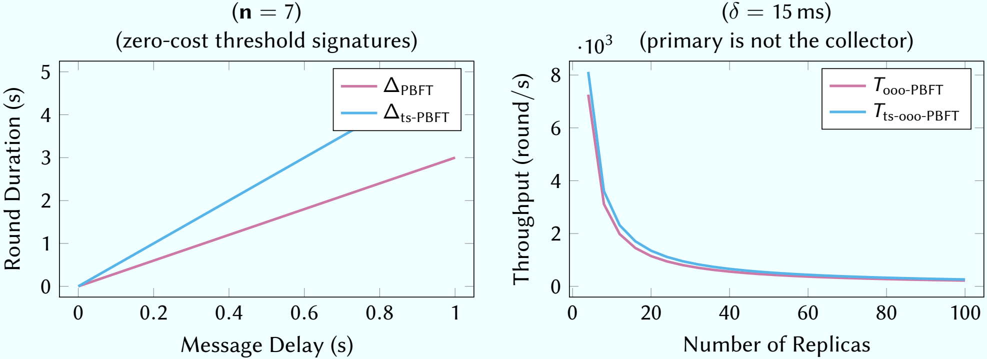
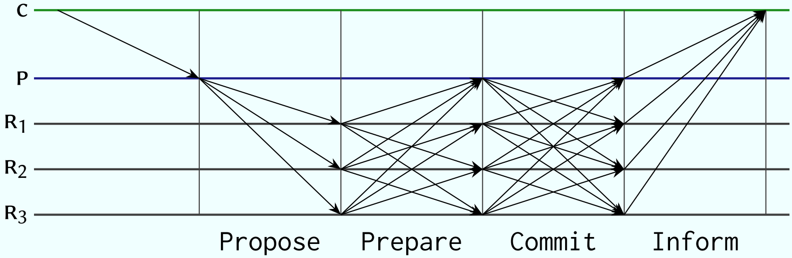


Limitations of Primary-Backup Consensus



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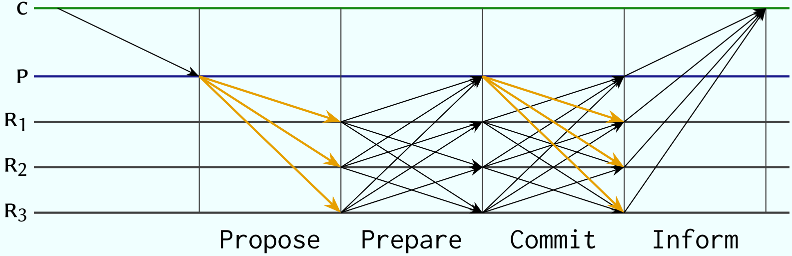

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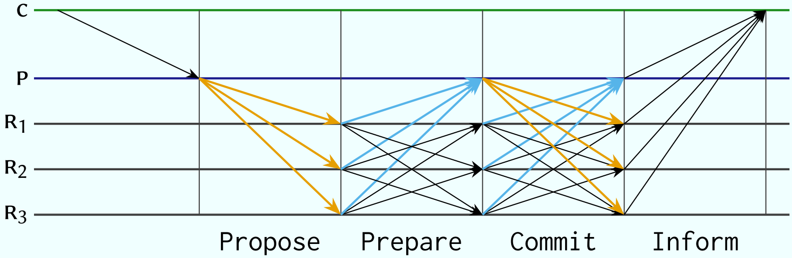

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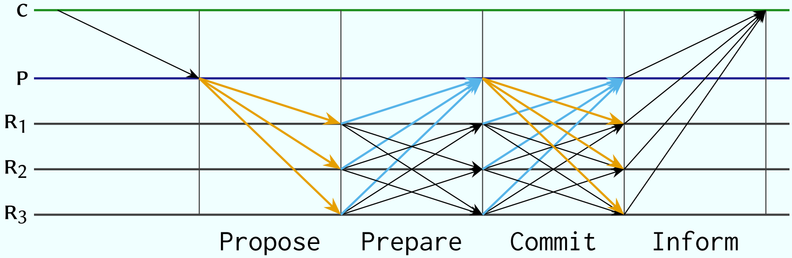

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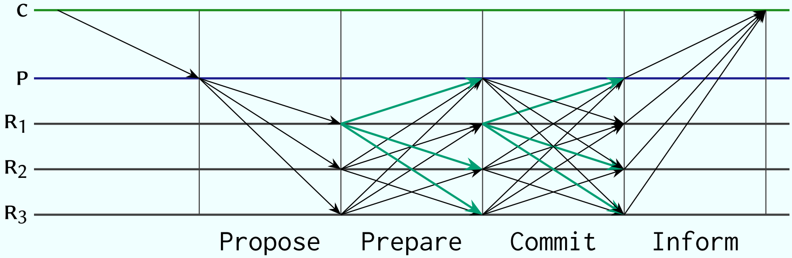

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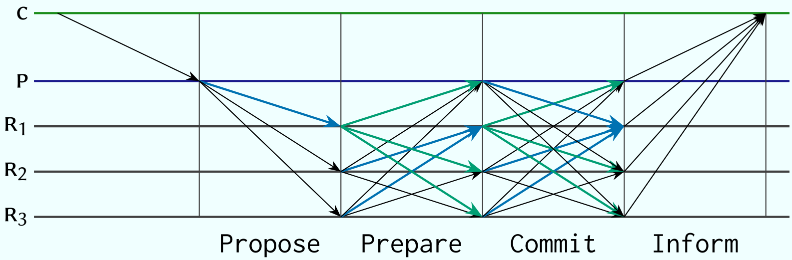

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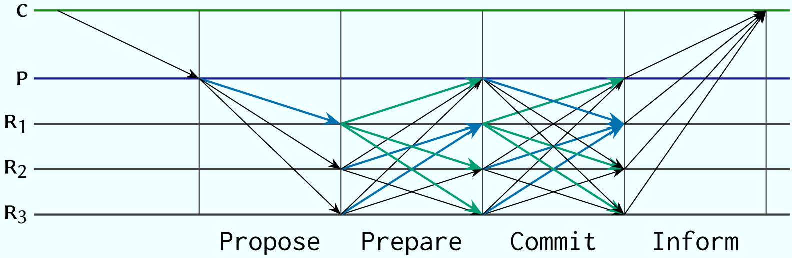

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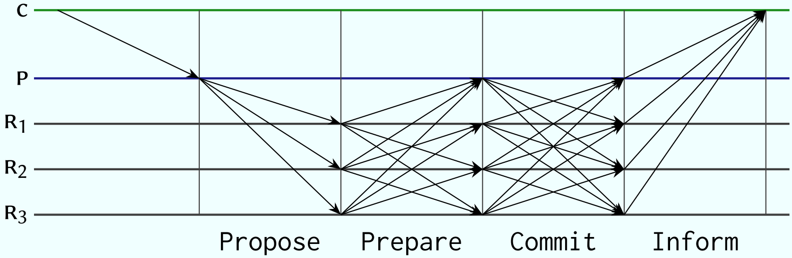

Bandwidth ratio between primary and backups

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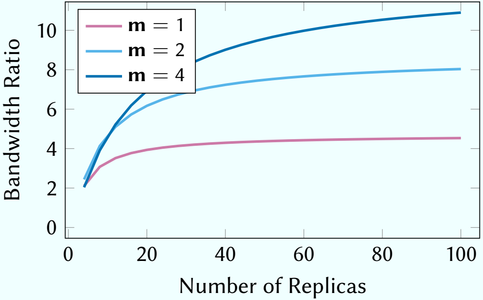

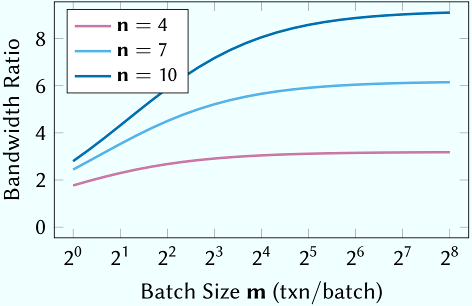

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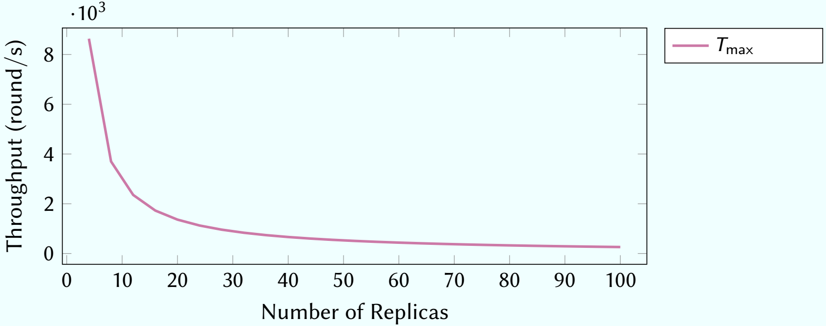

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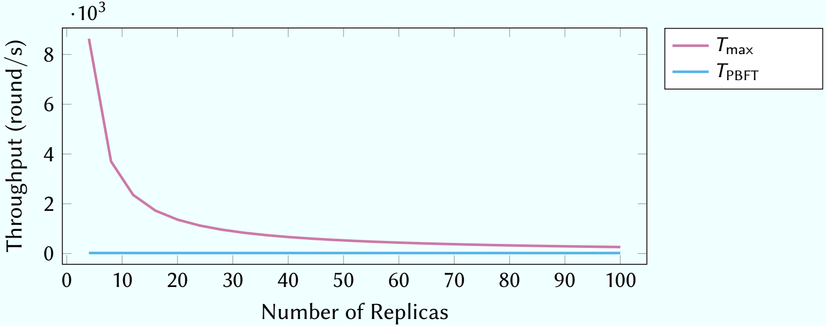

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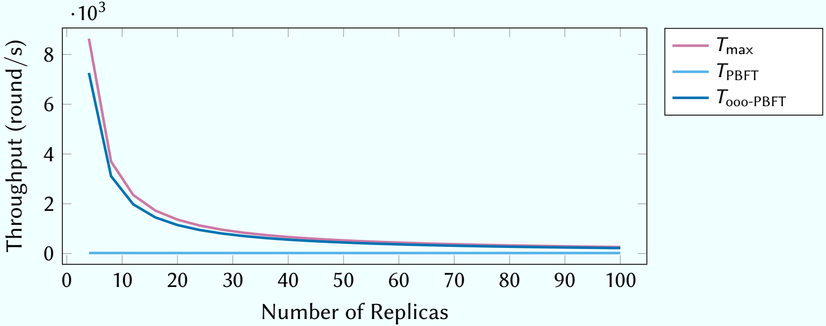

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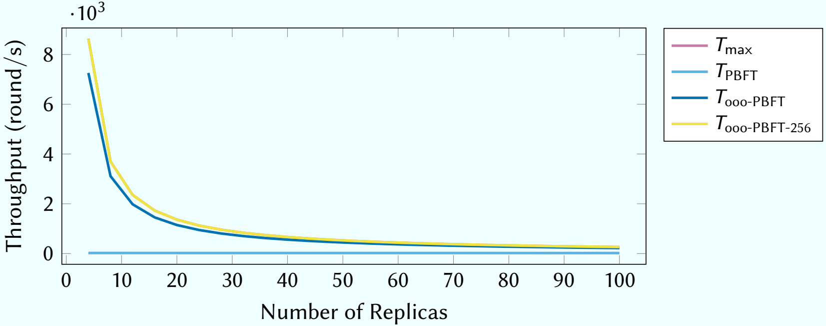

Concurrent Consensus

Idea: Multiple instances of PBFT, each with a distinct primary

$1 \leq \mathbf{z} \leq \mathbf{n}$ primaries: $\mathbf{z}$ simultaneous rounds of consensus that decide the next $\mathbf{z}$ requests.

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$$T_{\text{c-ooo-PBFT-}(\mathbf{z},\mathbf{m})} = \frac{\mathbf{z}\mathbf{m}B}{(\mathbf{m}(\mathbf{n}-1)s_{\mathrm{t}} + 3(\mathbf{n}-1)s_{\mathrm{m}}) + ((\mathbf{z}-1)(\mathbf{m}s_{\mathrm{t}} + 4(\mathbf{n}-1)s_{\mathrm{m}} - s_{\mathrm{m}}))}.$$

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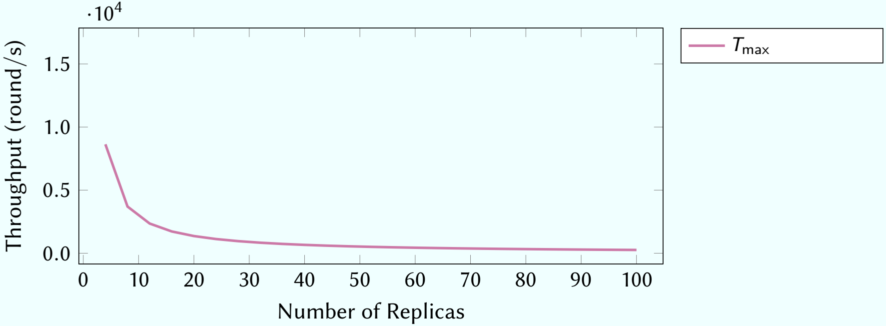

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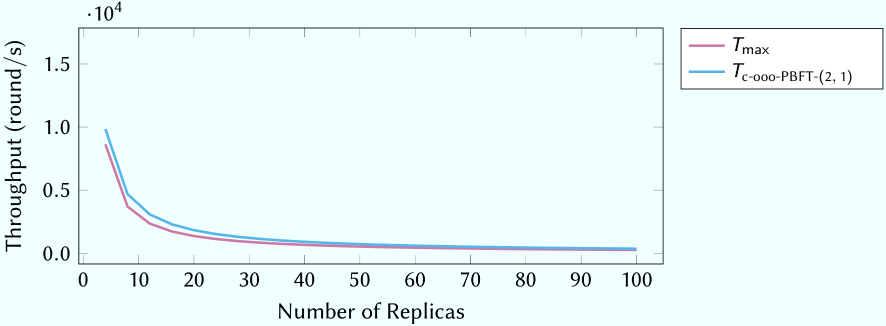

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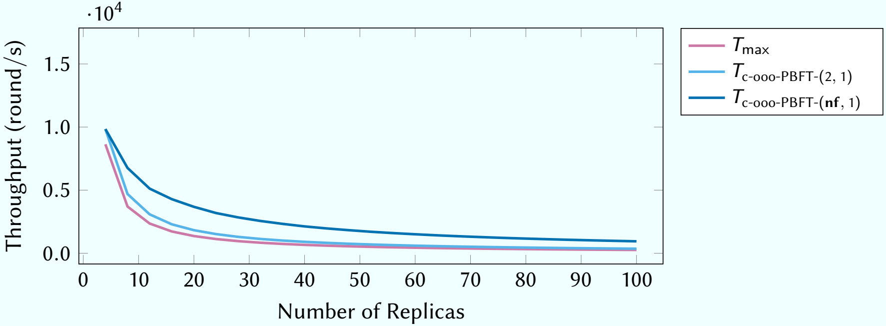
$$T_{\text{c-ooo-PBFT-}(\mathbf{z},\mathbf{m})} = \frac{\mathbf{z}\mathbf{m}B}{(\mathbf{m}(\mathbf{n}-1)s_{\mathrm{t}} + 3(\mathbf{n}-1)s_{\mathrm{m}}) + ((\mathbf{z}-1)(\mathbf{m}s_{\mathrm{t}} + 4(\mathbf{n}-1)s_{\mathrm{m}} - s_{\mathrm{m}}))}.$$

Assumption: $B = 100\,\mathrm{MiB/s}$, $s_{\mathrm{t}} = 4048\,\mathrm{B}$, $s_{\mathrm{m}} = 256\,\mathrm{B}$



Concurrent Consensus

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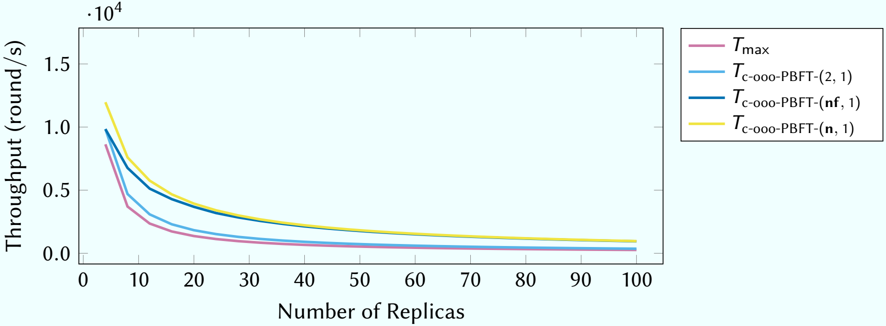

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