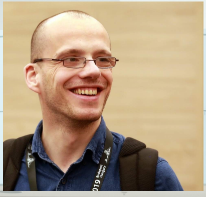
Fault-Tolerant Distributed Transactions on Blockchain

Beyond the Design of PBFT


Suyash Gupta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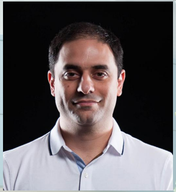
Mohammad Sadoghi

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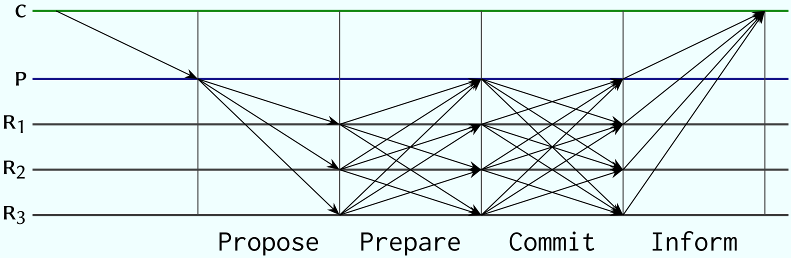
Previously: PBFT



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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Failure Model	The types of failures consensus can deal with.
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.
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Computational speed	determines the speed by which messages are processed.

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- Bottlenecks *outside consensus*: speed by which replicas *execute transactions*.
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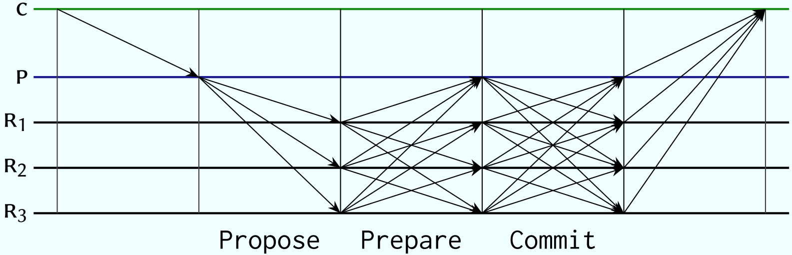
Bottleneck in practice: consensus performance in terms of throughput and latency (as a function of *network bandwidth* and *message delay*).

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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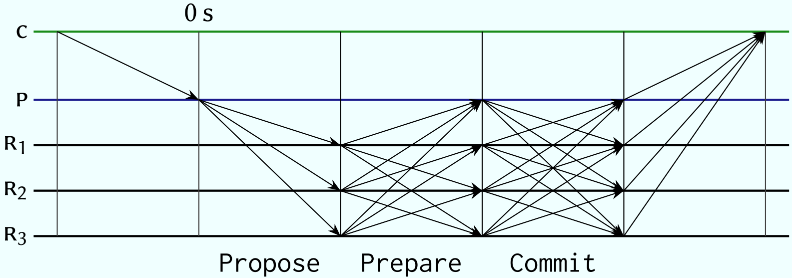
Propose: $s_t = 4048\,\mathrm{B}$ each.



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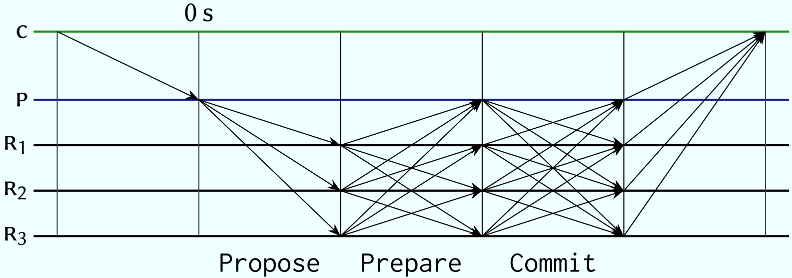

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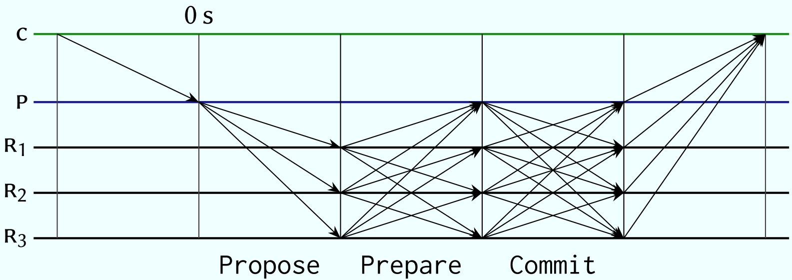

$$\left.\begin{array}{l} \blacktriangleright\ \mathbf{n} - 1 \text{ messages} \\ \blacktriangleright\ s_t \text{ B each} \end{array}\right\} (\mathbf{n} - 1)s_t = 3 \cdot 4048 = 12\,144\,\mathrm{B}$$

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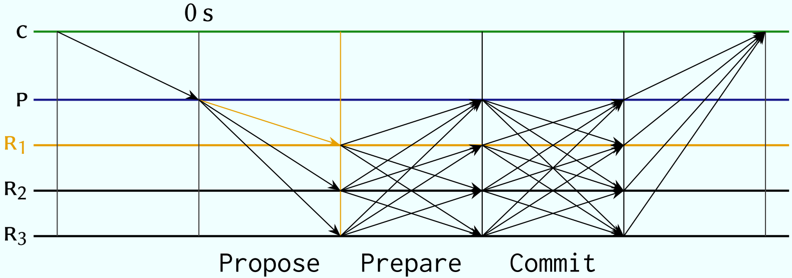

- $\mathbf{n} - 1$ messages
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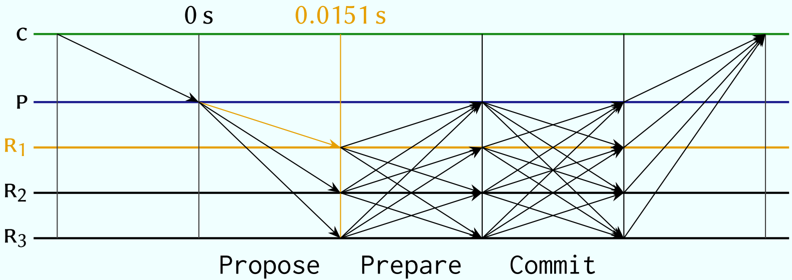

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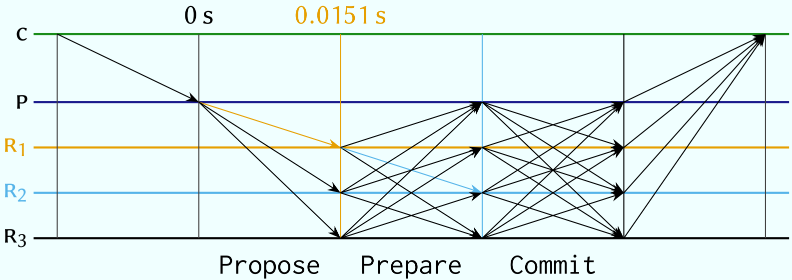
$$\frac{(\mathbf{n}-1)s_t}{B} + \delta = \frac{12144}{100 \cdot 2^{20}} + 0.015 \approx 0.0151\,\mathrm{s}.$$

The Single-Round Cost of PBFT (Sketch)

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

`Propose`: $s_t = 4048$ B each. `Prepare` and `Commit`: $s_m = 256$ B each.



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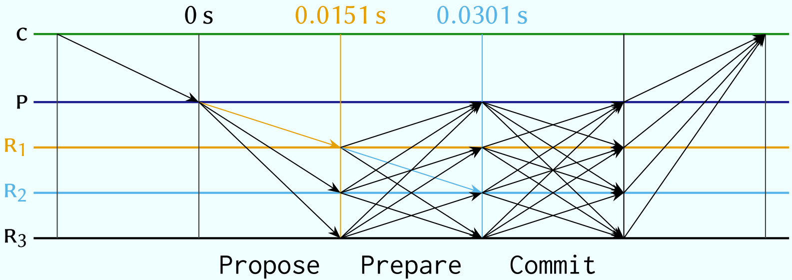

- **n** − 1 messages
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$$\frac{(\mathbf{n}-1)s_m}{B} + \delta = \frac{768}{100 \cdot 2^{20}} + 0.015 \approx 0.0150\text{ s}.$$

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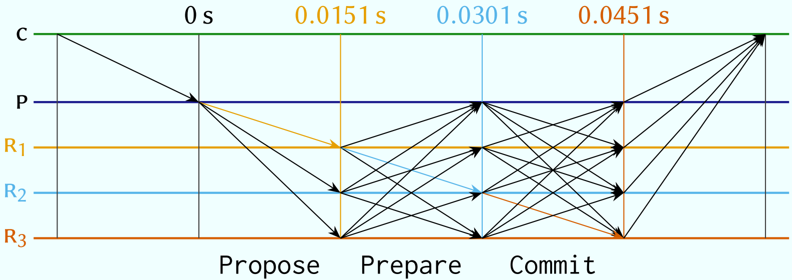

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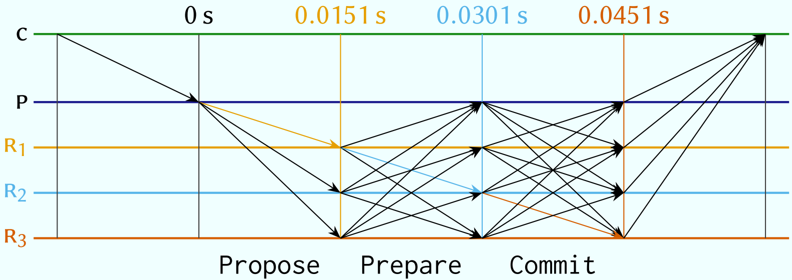

$\Delta_{\text{PBFT}} =$

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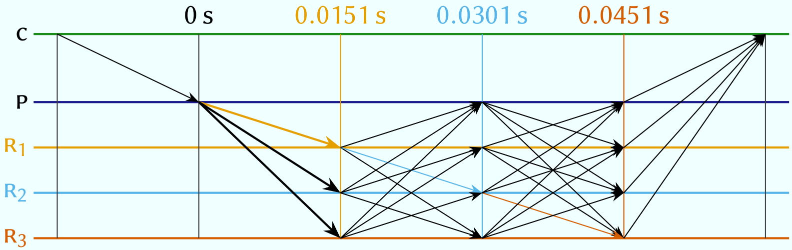

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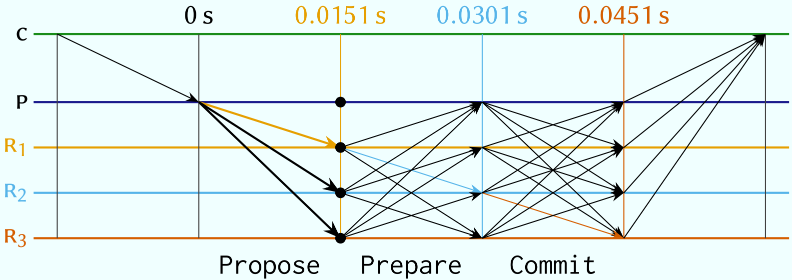

$$\Delta_{\mathrm{PBFT}} = \frac{(\mathbf{n} - 1)s_t}{B} + \delta$$

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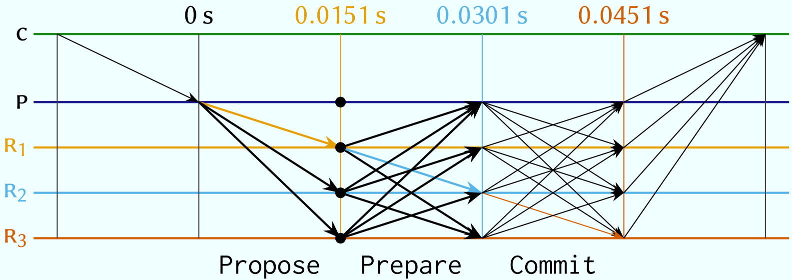

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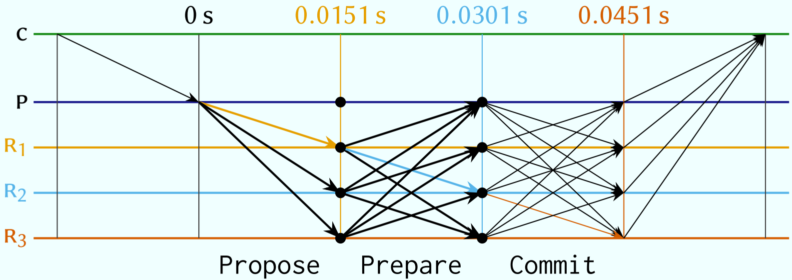

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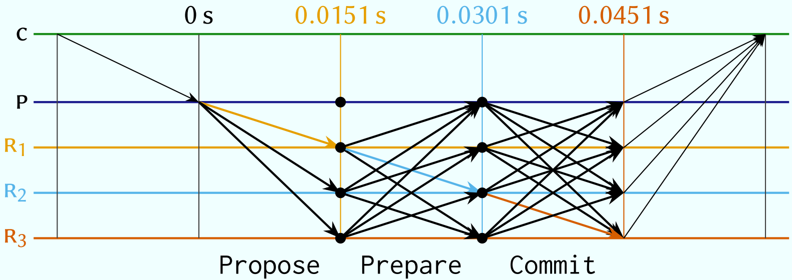

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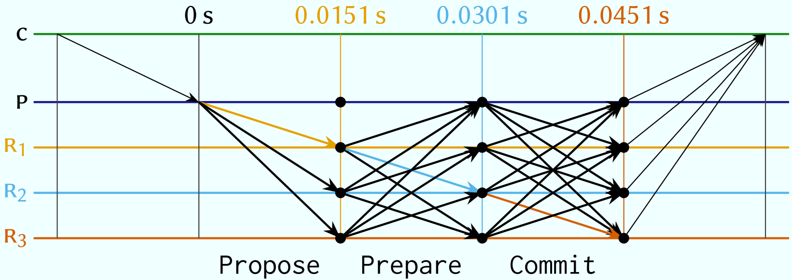

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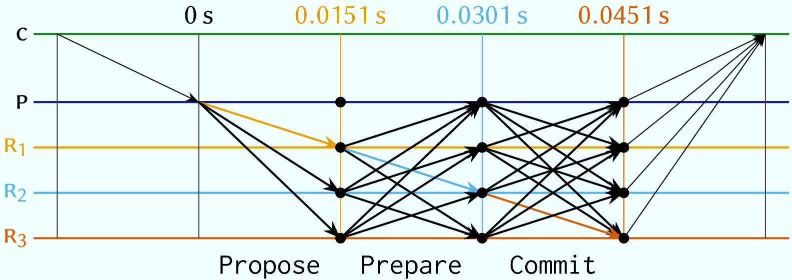

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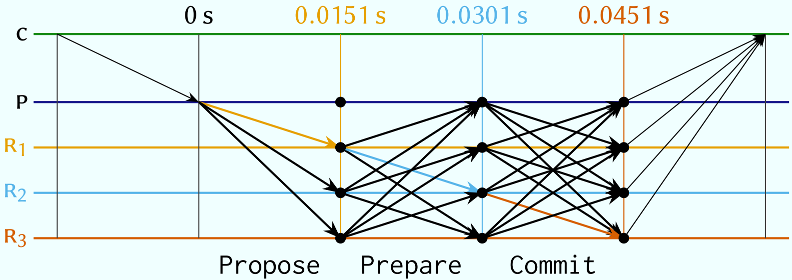

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$\approx 3\delta$ (assuming *high delay relative to bandwidth*).

The Throughput of PBFT

Sequential: Next consensus round starts after finishing the current round

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

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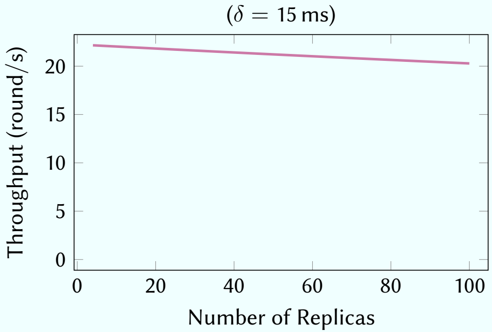

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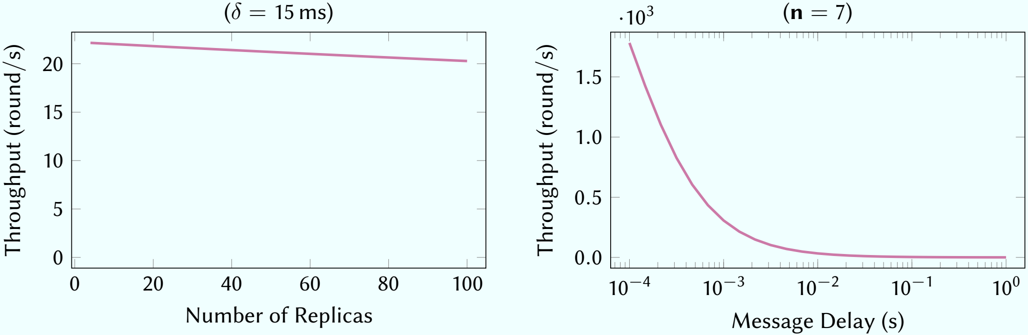

Implementation techniques for PBFT

Realistic wide-area message delays: 10 ms–300 ms

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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}

Batching Client Requests

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

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`Propose`	Primary	s_{t}	ms_{t}
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`Commit`	All	s_{m}	s_{m}

Batching Client Requests

The cost of a single round of PBFT

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

Message	Sent by	Size	*(batch)*
`Propose`	Primary	s_{t}	$m s_{\mathrm{t}}$
`Prepare`	Backups	s_{m}	s_{m}
`Commit`	All	s_{m}	s_{m}
Total:	$2\mathbf{n}(\mathbf{n}-1)$	$\mathcal{O}(s_{\mathrm{t}}\mathbf{n} + s_{\mathrm{m}}\mathbf{n}^2)$	$\mathcal{O}(m s_{\mathrm{t}}\mathbf{n} + s_{\mathrm{m}}\mathbf{n}^2)$

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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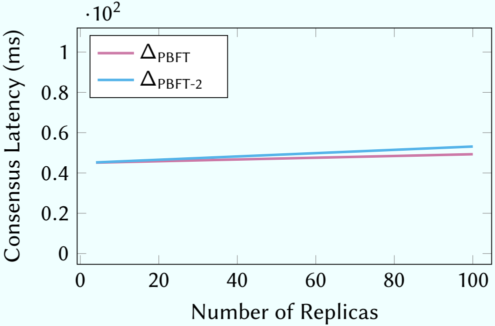

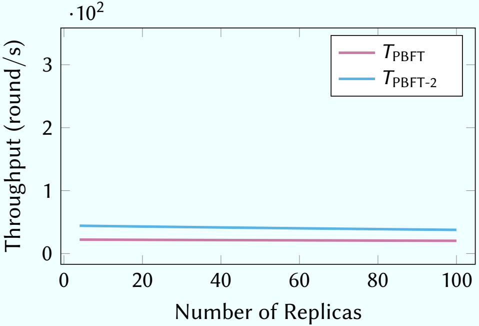

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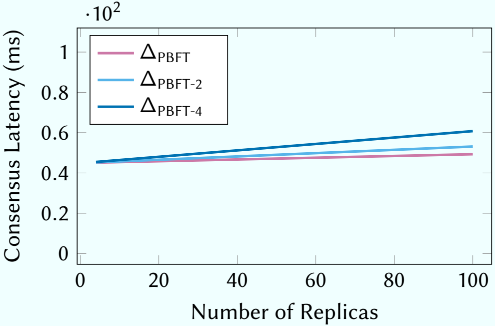

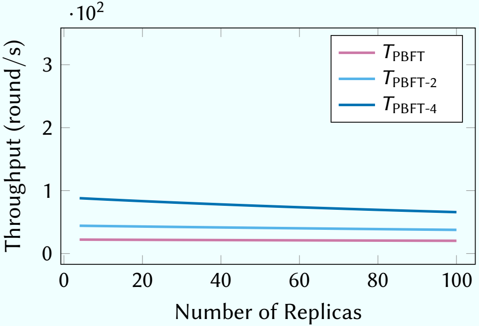

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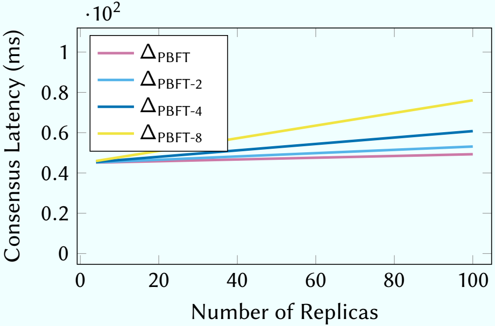

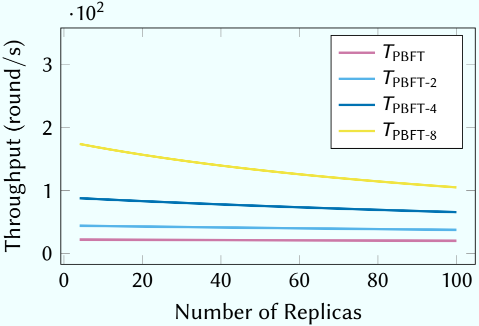

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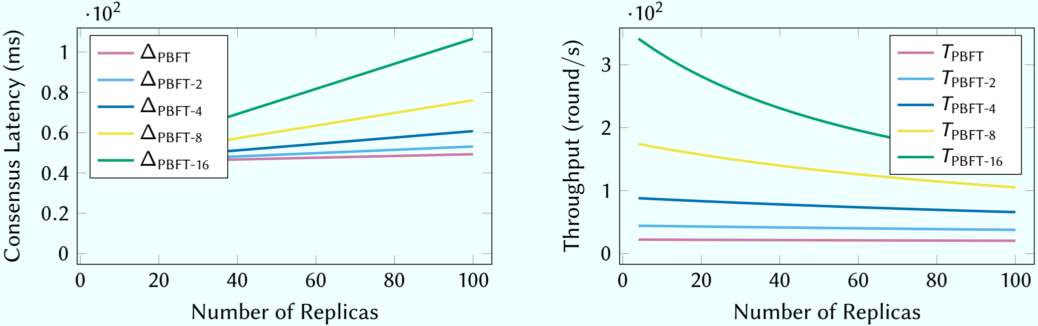
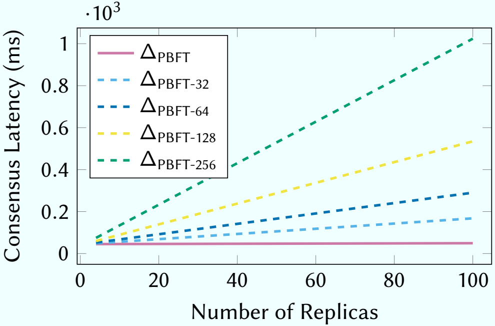


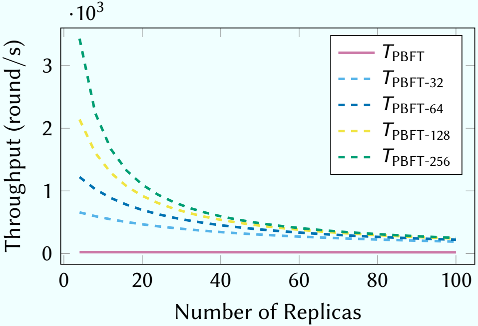
The Throughput of PBFT with Batching

Sequential, batching m transactions per consensus round

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

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





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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PBFT-$\mathbf{n}$	$2\mathbf{n}(\mathbf{n}-1)$	$2(\mathbf{n}-1)$	$\mathcal{O}(\mathbf{n}s_{\mathrm{t}}\mathbf{n}+s_{\mathrm{m}}\mathbf{n}^2)$	$\mathcal{O}(s_{\mathrm{t}}\mathbf{n}+s_{\mathrm{m}}\mathbf{n})$	

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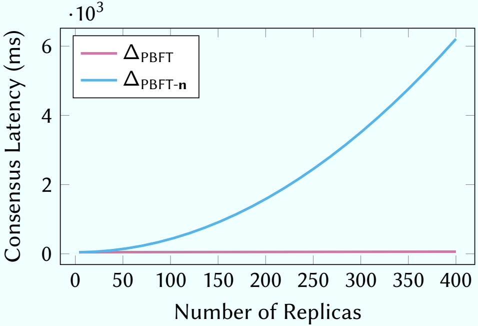

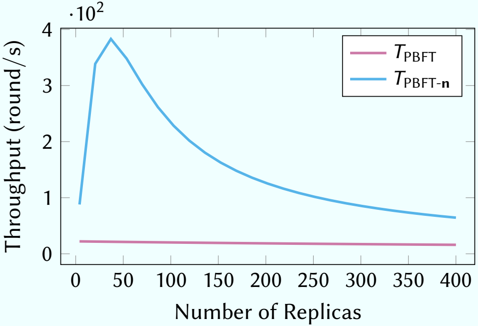

Resource Utilization of Sequential PBFT

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

$$\Delta_{\mathrm{PBFT}} = \frac{(\mathbf{n}-1)s_\mathrm{t} + 2(\mathbf{n}-1)s_\mathrm{m}}{B} + 3\delta \approx 45.1\,\mathrm{ms}.$$

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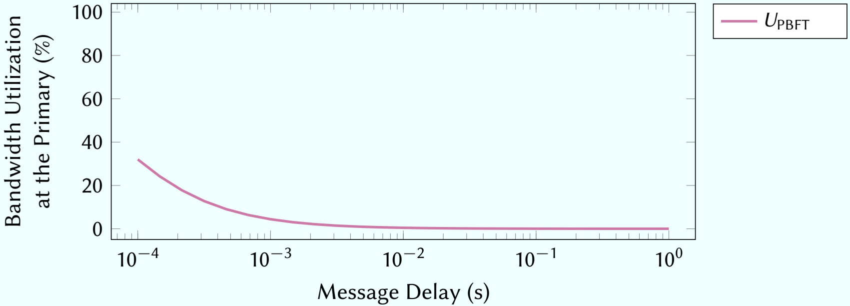

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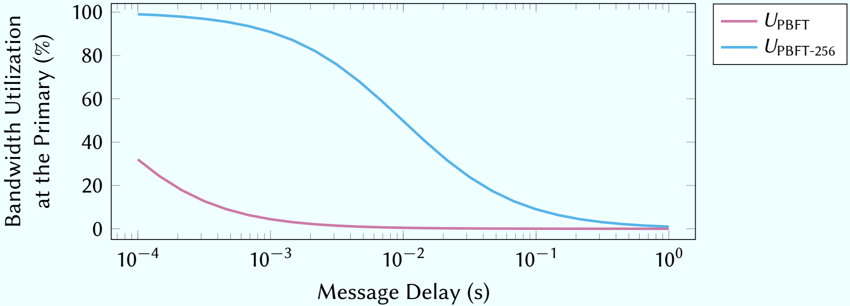

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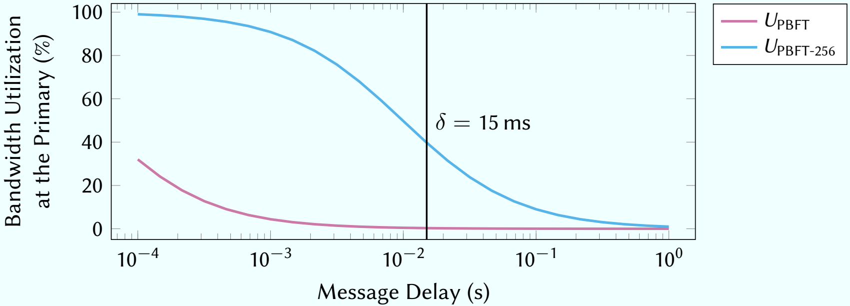

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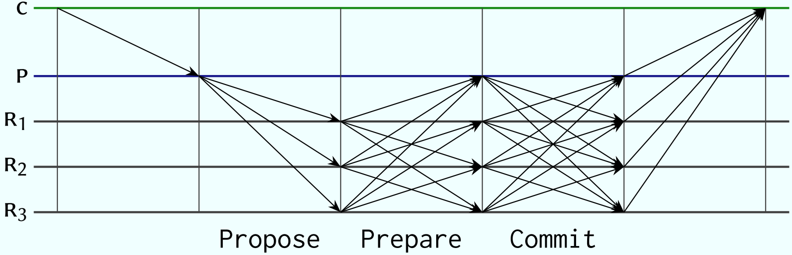
Limit proposals to an *active window* of valid rounds.
E.g., only proposals in 1000 rounds after the last finished round.

The Single-Round Cost of PBFT (revised)

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



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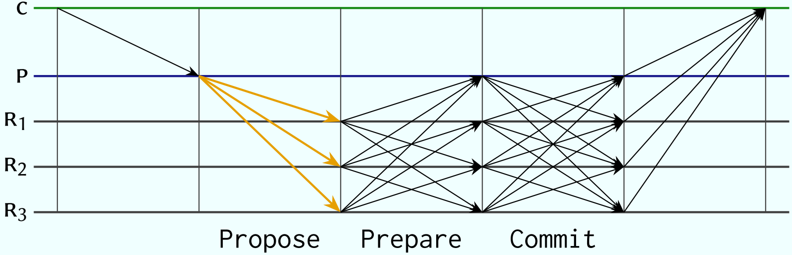

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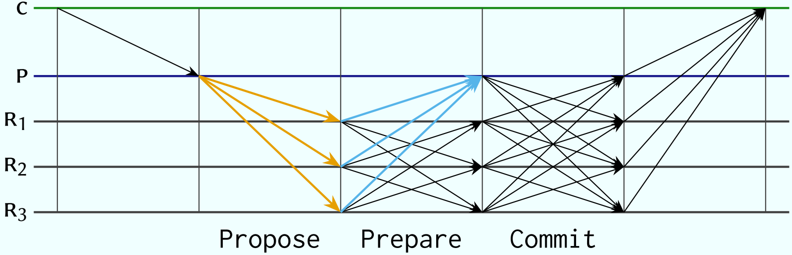

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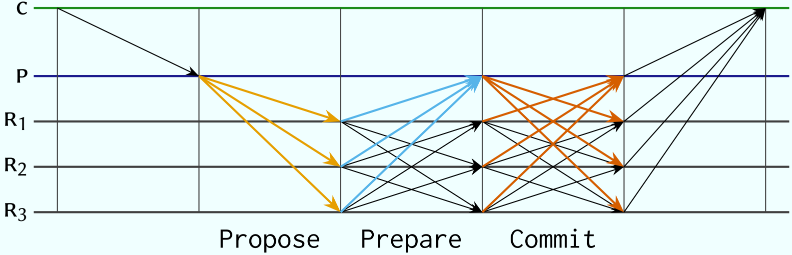

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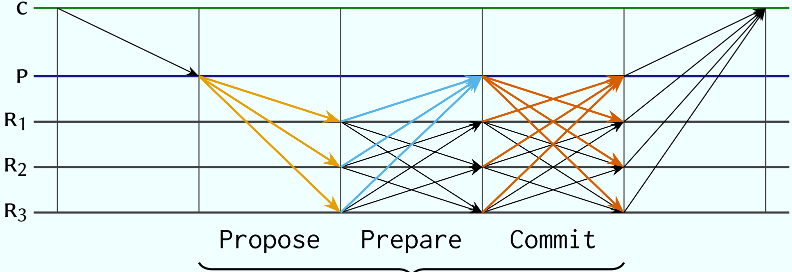

$$(\mathbf{n}-1)s_t + (\mathbf{n}-1)s_m + 2(\mathbf{n}-1)s_m = (\mathbf{n}-1)(s_t + 3s_m)\ \mathrm{B/round.}$$

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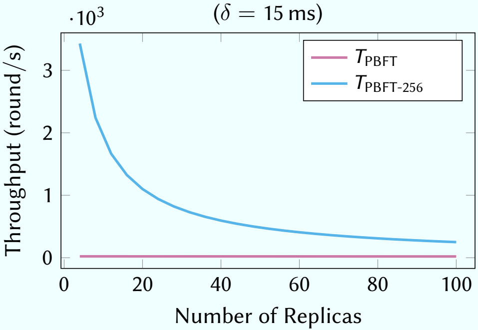

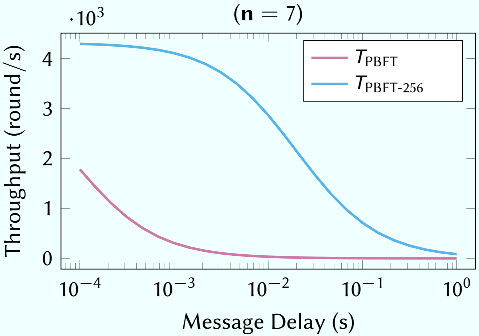

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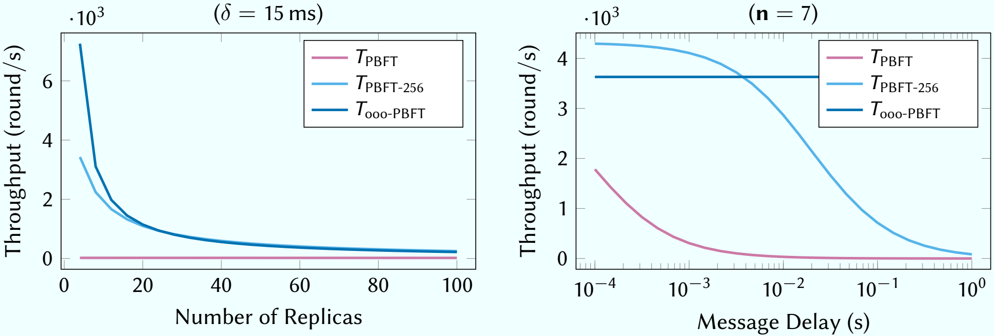

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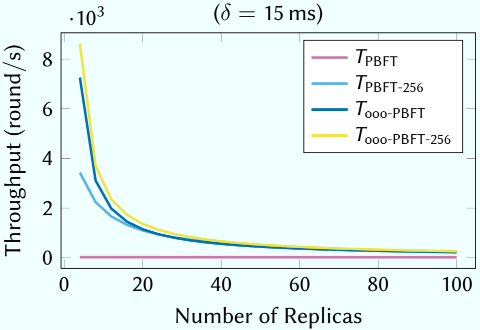

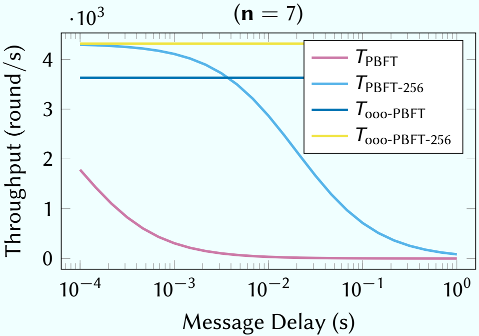

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Implies strict consecutive processing of rounds

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

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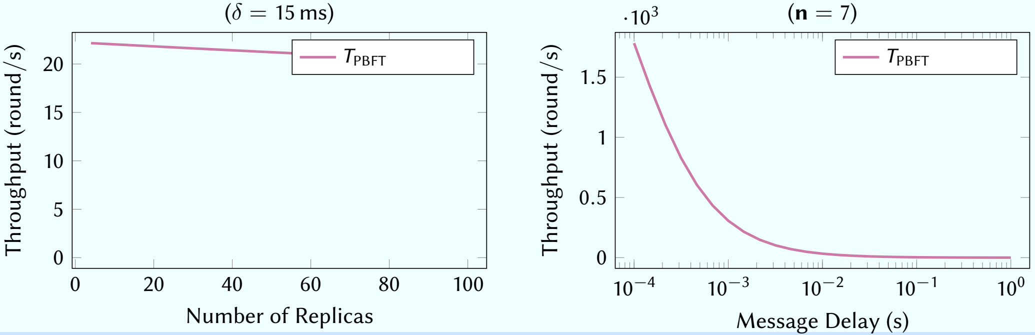

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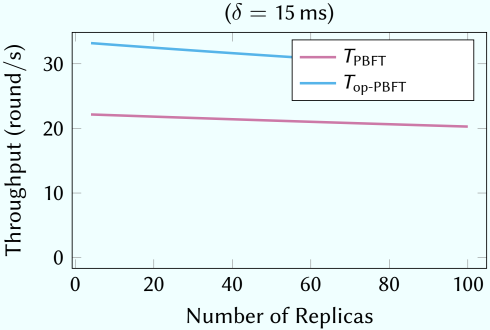

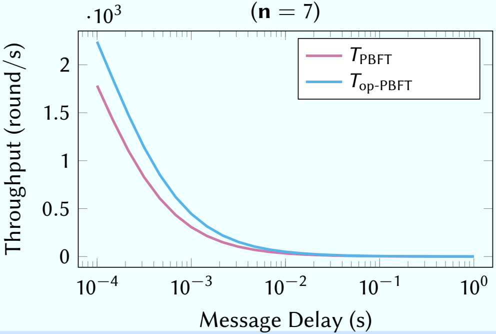

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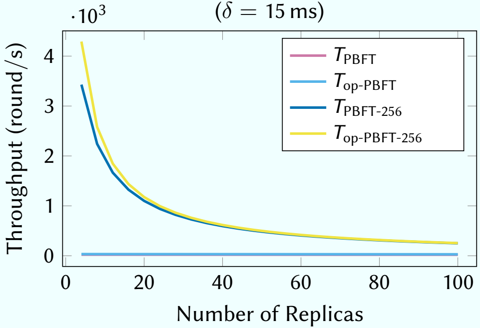

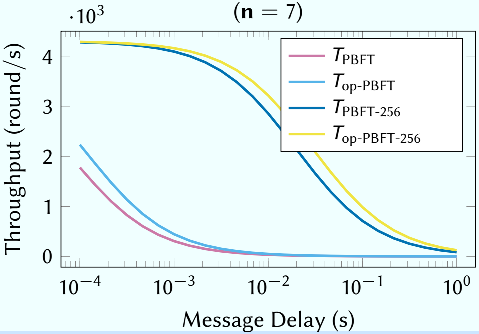

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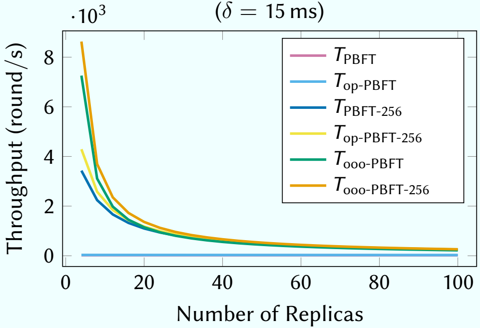

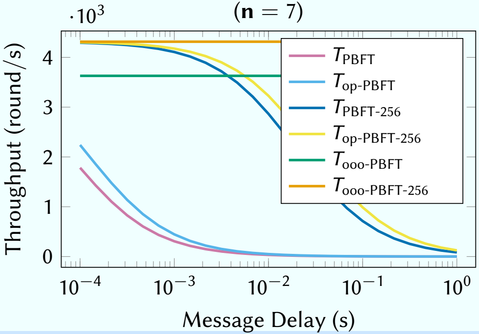

Implementation techniques for PBFT: Summary

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

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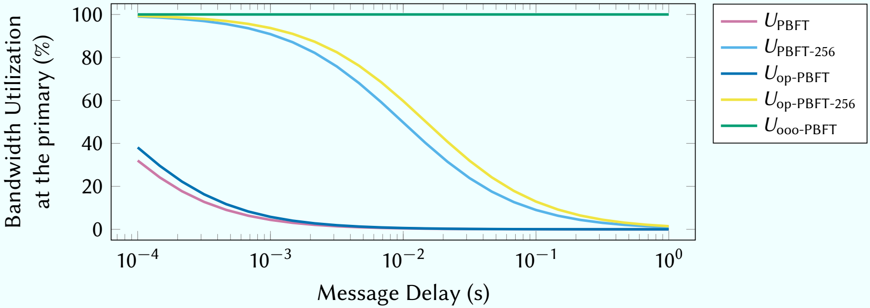

Primary-backup Consensus Beyond PBFT

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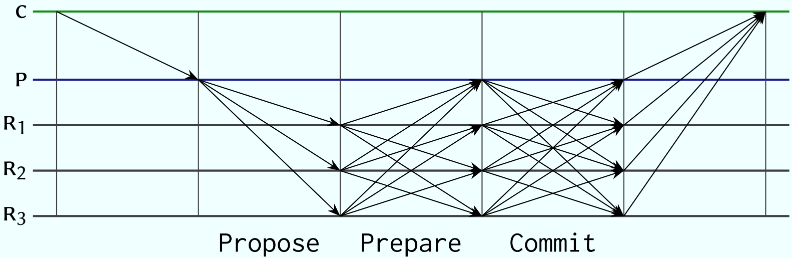
Technologies employed by PBFT-like consensus

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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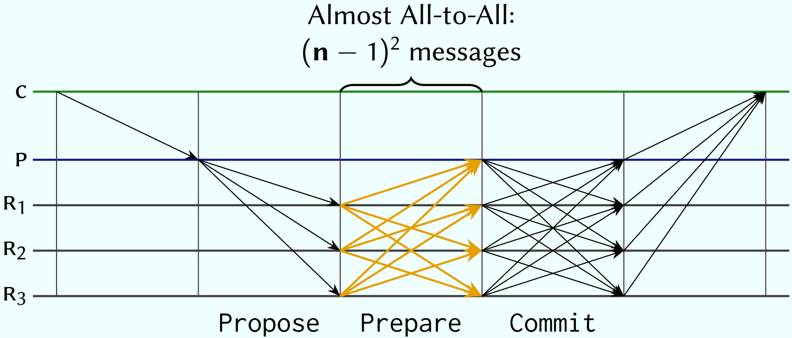

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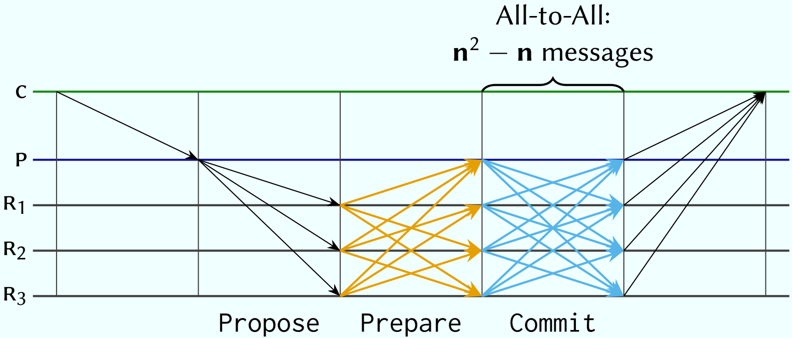

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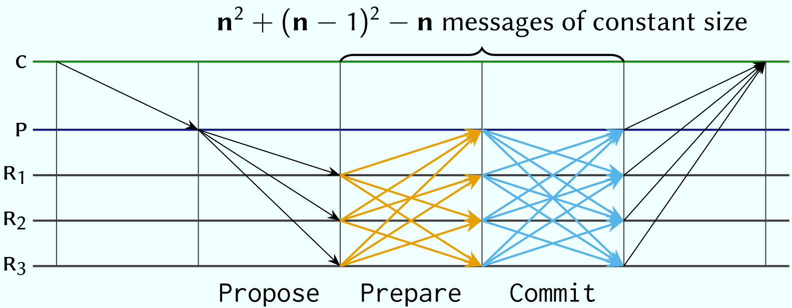

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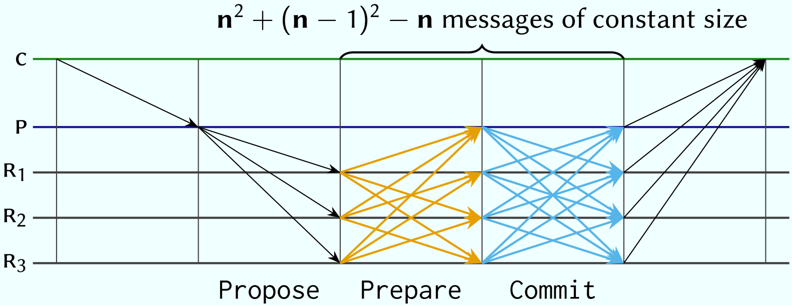
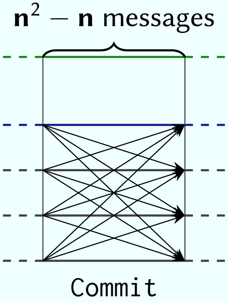


Challenge: Reduce communication from $\mathcal{O}(\mathbf{n}^2)$ to $\mathcal{O}(\mathbf{n})$ *messages of constant size*.

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

Consider the commit phase



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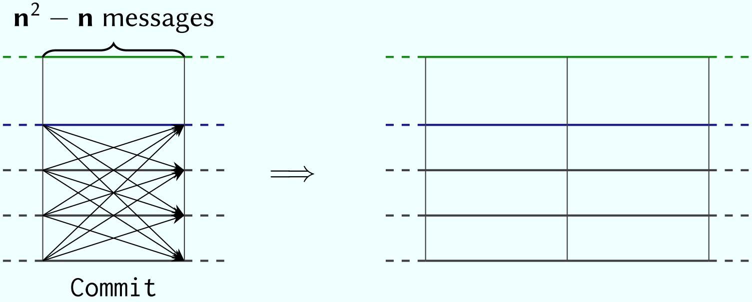

Idea: All replicas send to *one aggregator* that then sends to all replicas.

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

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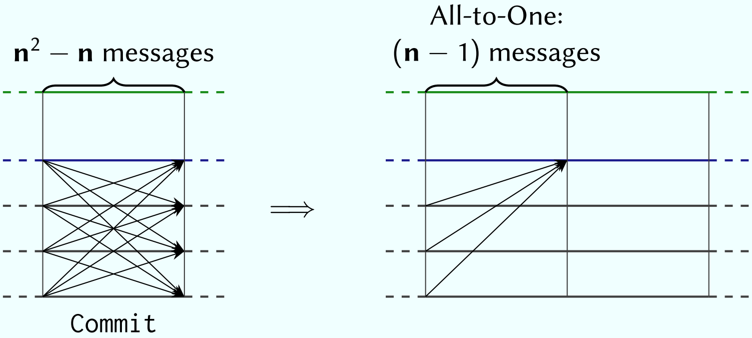

Idea: All replicas send to *one aggregator* that then sends to all replicas.

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

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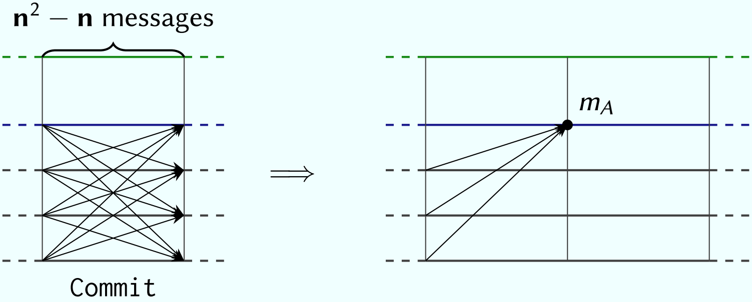

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2. The aggregator combines $\mathbf{n} - \mathbf{f}$ `Commit` messages into an aggregated message m_A.

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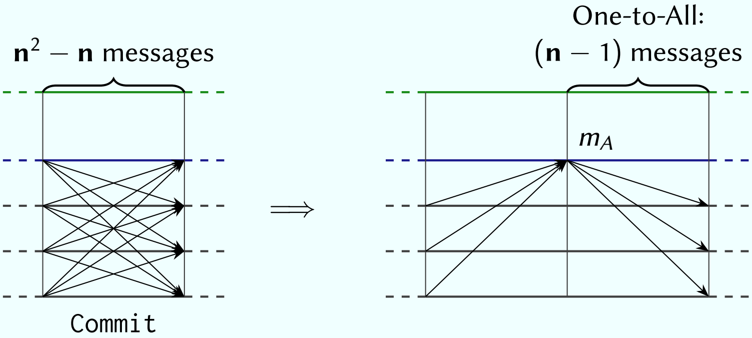

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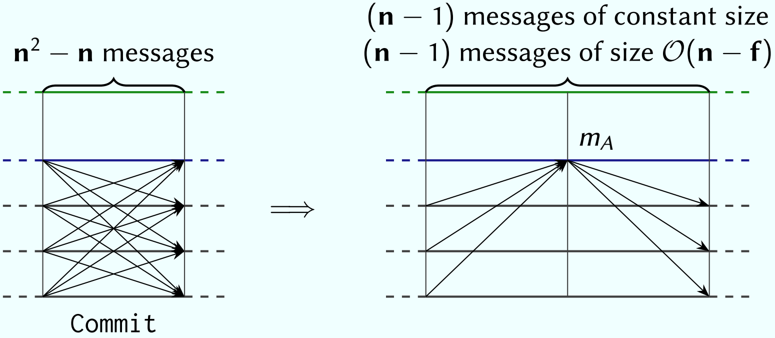

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3. The aggregator sends m_A to all replicas *of size* $\mathcal{O}(\mathbf{n} - \mathbf{f})$ *each*.

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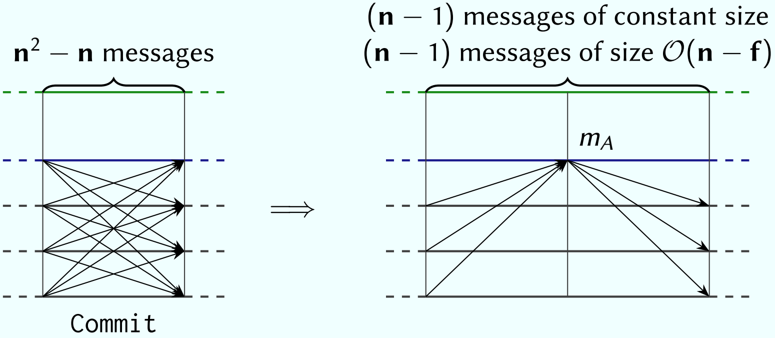

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Effectively reduced communication from $\mathcal{O}(\mathbf{n}^2)$ to $\mathcal{O}(\mathbf{n}(\mathbf{n} - \mathbf{f}))$.

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.
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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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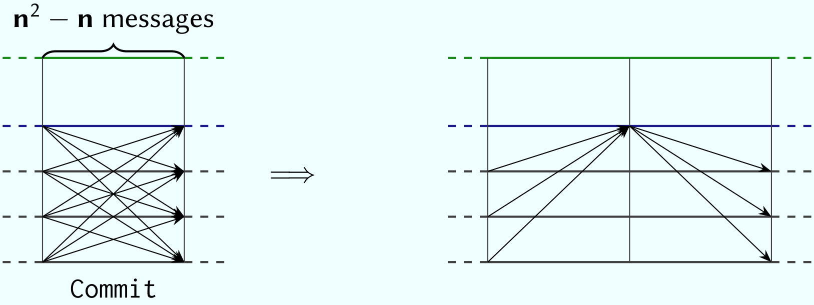

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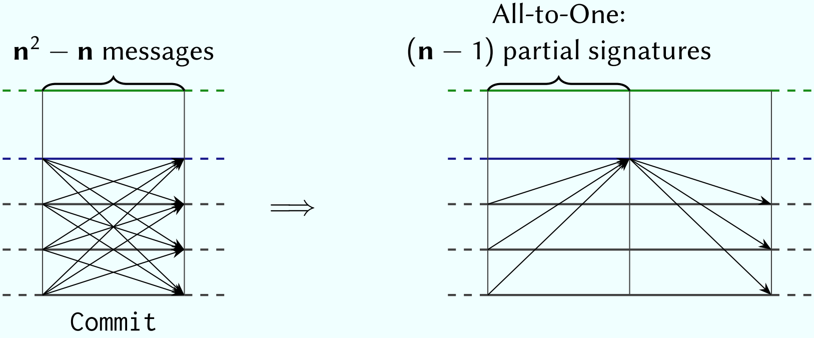

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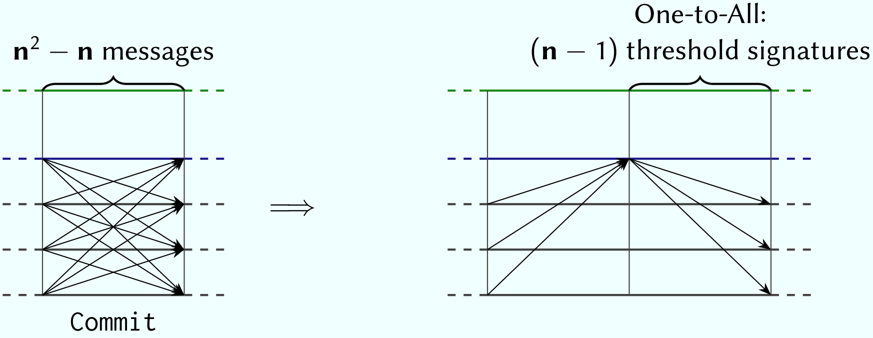

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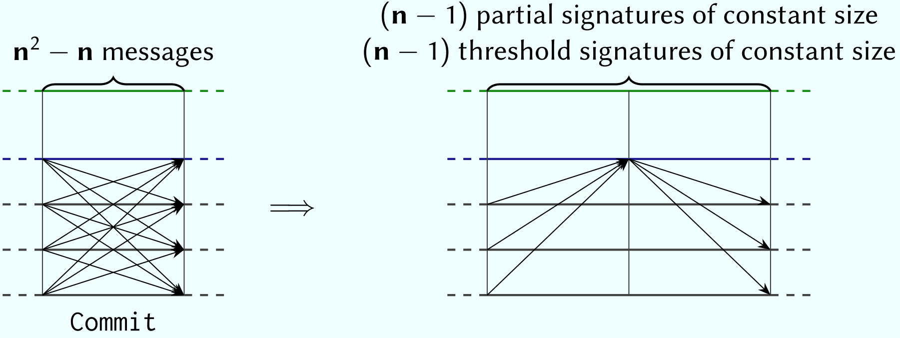

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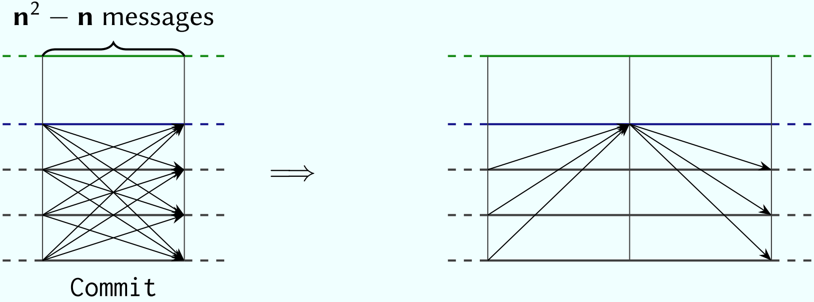

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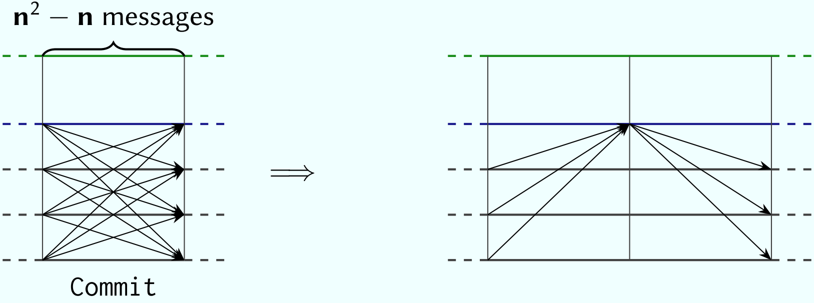

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Similar change can be made to the prepare phase.

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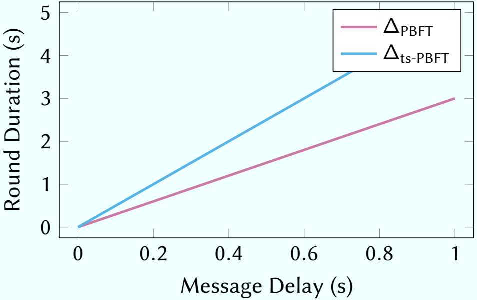
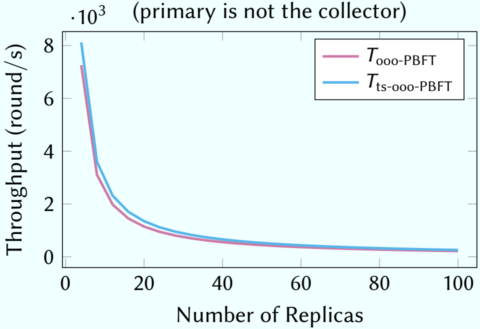
Assumption: $B = 100\,\text{MiB}/\text{s}$, $s_\text{t} = 4048\,\text{B}$, $s_\text{m} = 256\,\text{B}$

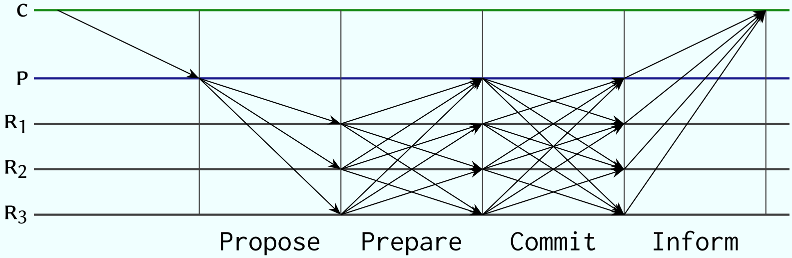
($\mathbf{n} = 7$)
(zero-cost threshold signatures)



($\delta = 15\,\text{ms}$)
(primary is not the collector)



Limitations of Primary-Backup Consensus



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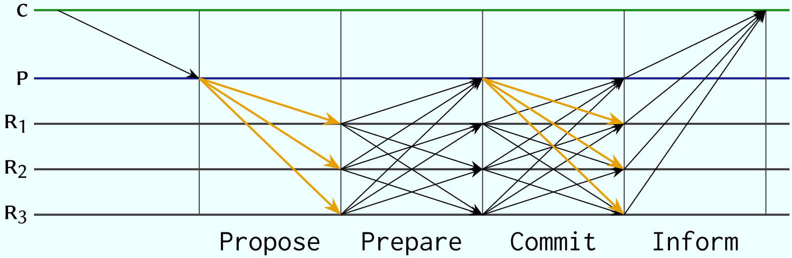

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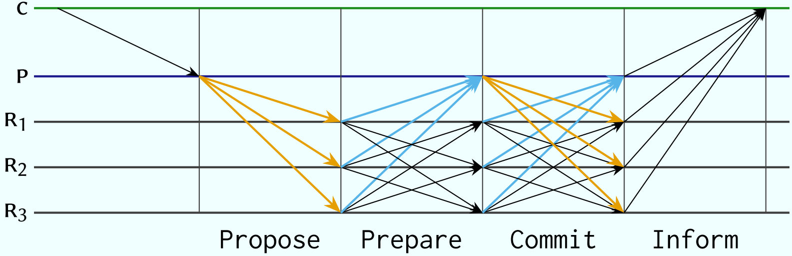

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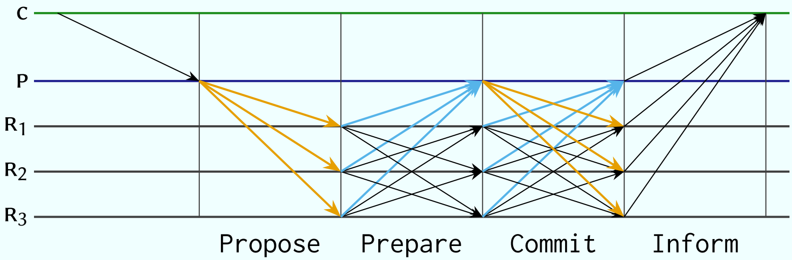

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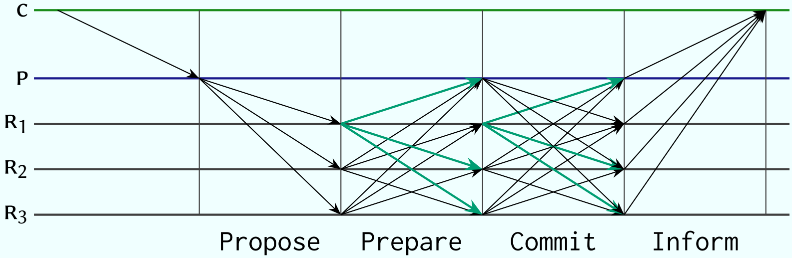

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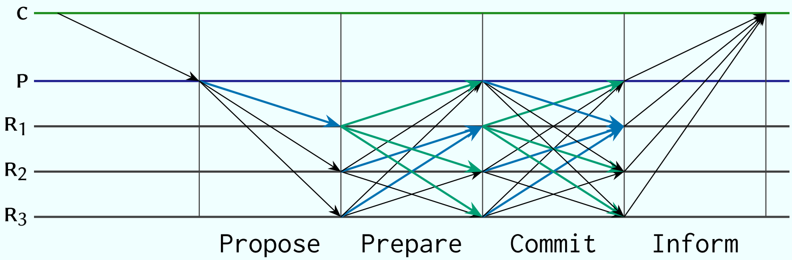

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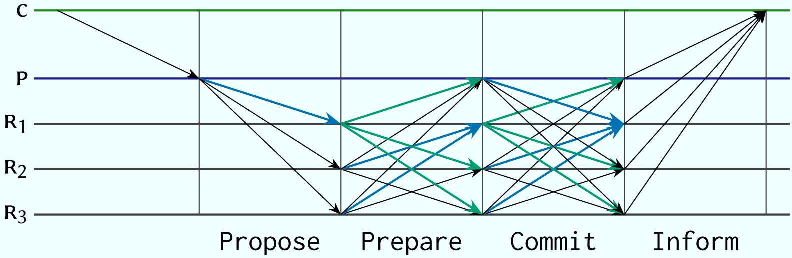

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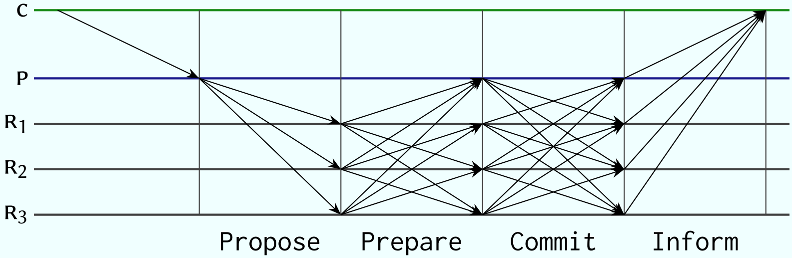

Bandwidth ratio between primary and backups

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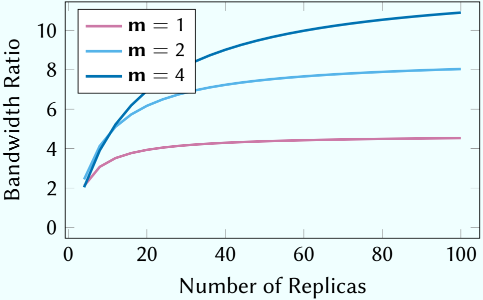

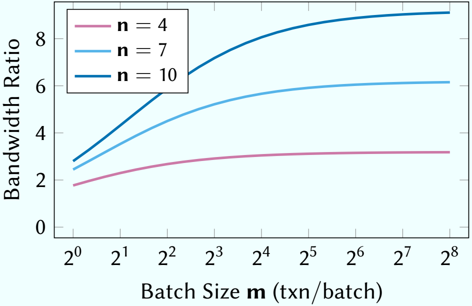

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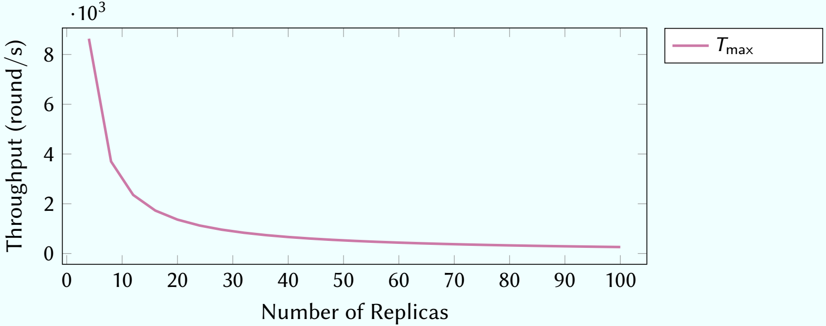

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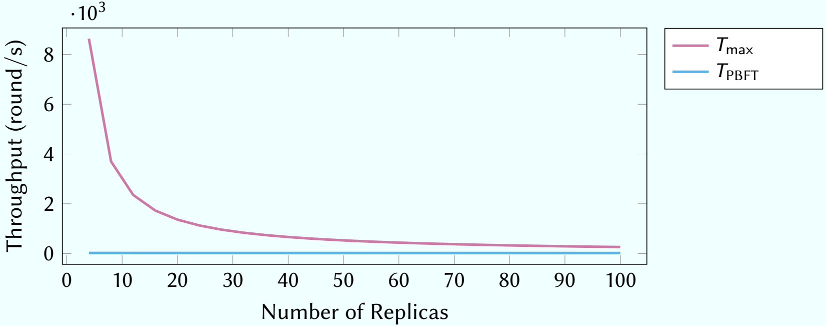

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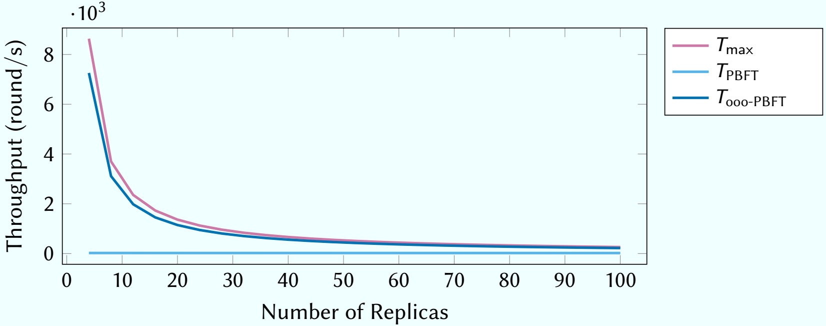

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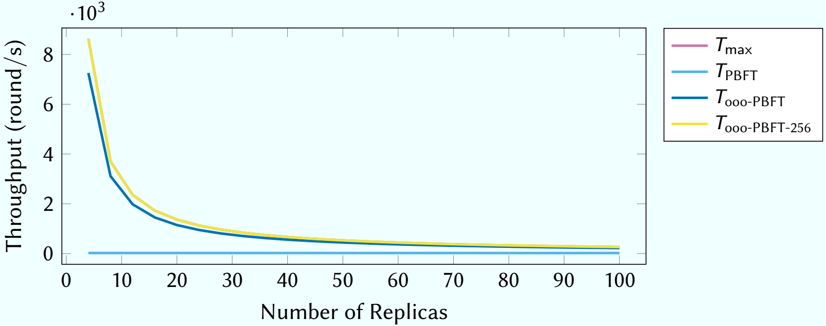

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Idea: Multiple instances of PBFT, each with a distinct primary

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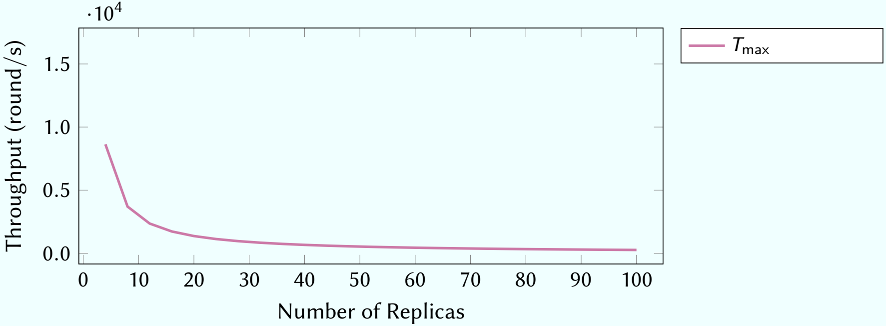

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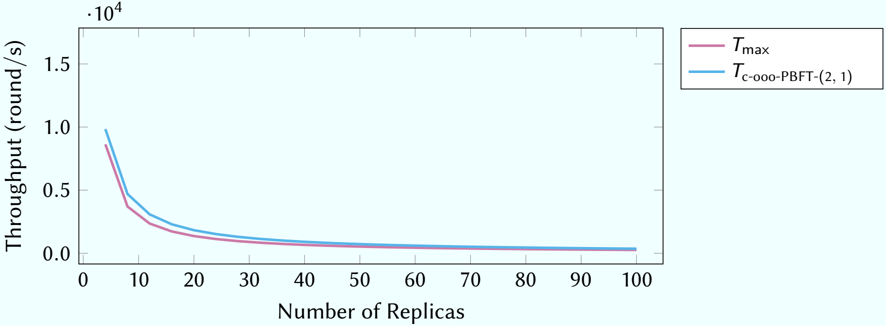

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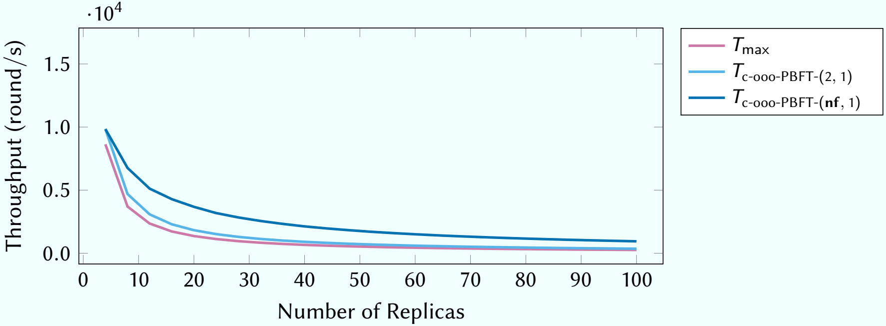

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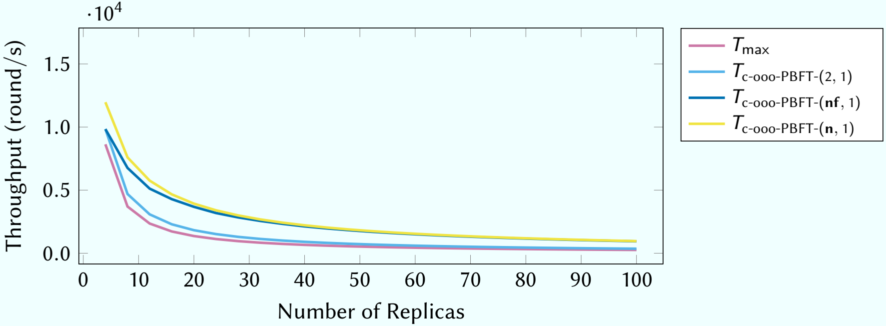
$1 \leq \mathbf{z} \leq \mathbf{n}$ primaries: $\mathbf{z}$ simultaneous rounds of consensus that decide the next $\mathbf{z}$ requests.

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

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



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