WaterBear: Asynchronous BFT with Information-Theoretic Security and Quantum Security

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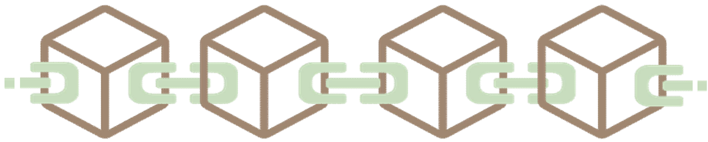
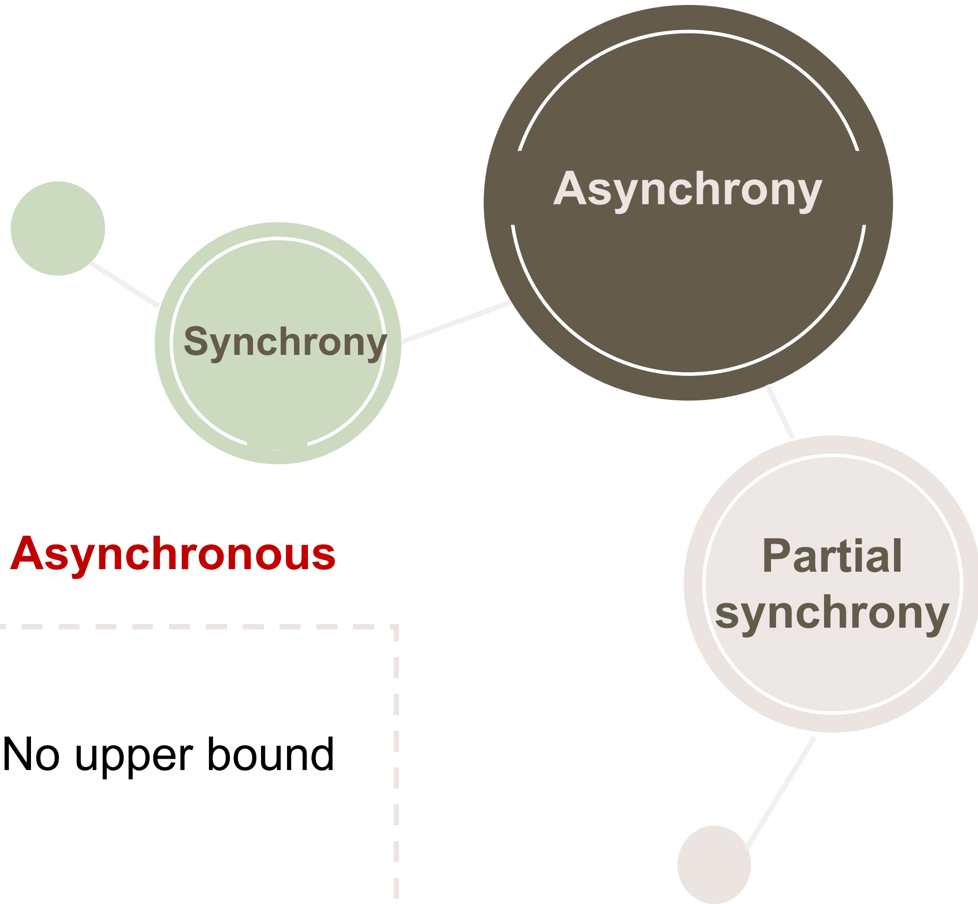
Byzantine Fault Tolerance (BFT)

- Building block for blockchains





- Timing assumptions

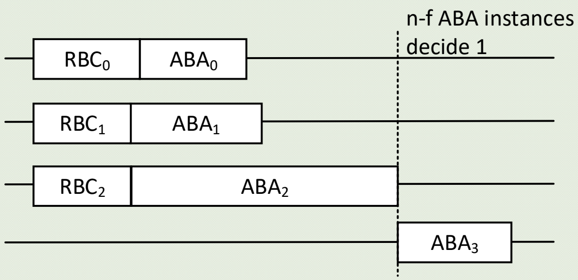
Synchronous	Partially Synchronous	Asynchronous
Known upper bound for message transmission /processing	Unknown upper bound	No upper bound

Background

- **Computational security**
  - The adversary is restricted to probabilisitc polynomial-time
- **Information-theoretic security**
  - The adversary is unbounded
  - Typically assuming secure or authenticated channels
- **Quantum security (no PKC)**
  - No public key cryptography (PKC)

Asynchronous BFT Paradigms

BKR



Ben-Or, Kemler, and Rabin (BKR)
PODC 1994

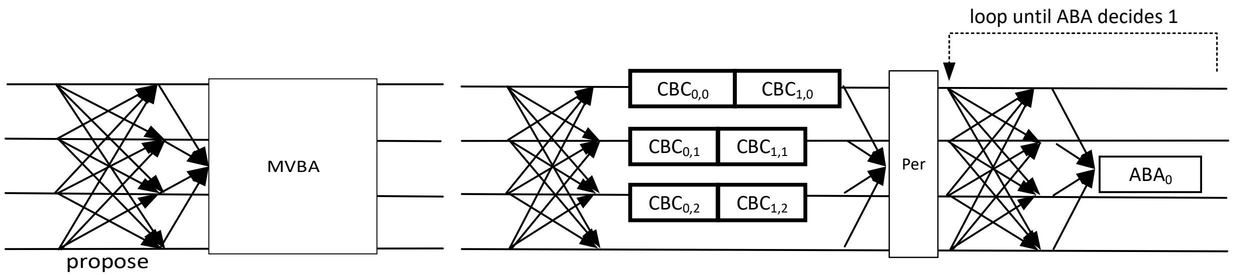
HoneyBadger CCS 2016	BEAT CCS 2018	EPIC DSN 2020	RedBelly S&P 2021

*assumes partial synchrony

$O(n^3)$ message	$O(Ln^2+\lambda n^3 \log n)$ communication	information-theoretic	$O(\log n)$ time
$O(n^2)$ message	$O(Ln^2+\lambda n^3 \log n)$ communication	Not information-theoretic	$O(1)$ time

CKPS

*$O(Ln2+\lambda n2)$ communication can be achieved theoretically

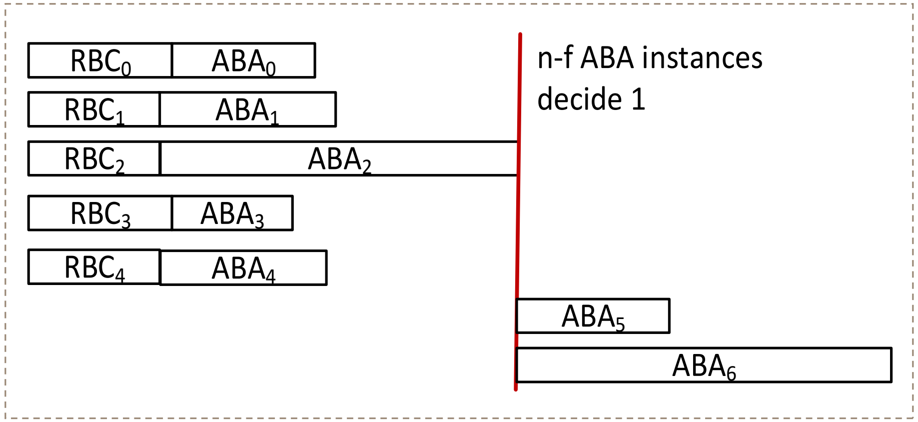


Cachin, Kusawe, Petzold, Shoup (CKPS)
CRYPTO 2001

Dumbo CCS 2020	Speeding Dumbo NDSS 2022

BKR (PODC 1994) -> PACE (CCS 2022)

BKR



ABA becomes the bottleneck

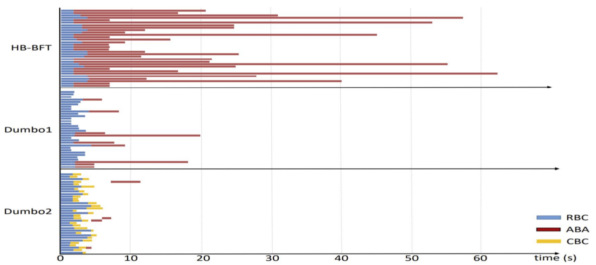
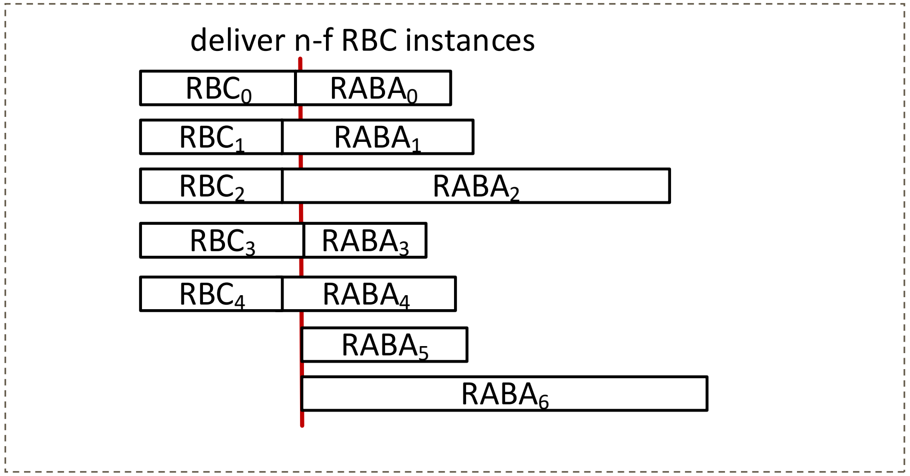


Fig. 5. Running time breakdown of Dumbo1/2 and HoneyBadgerBFT on one random node [6].

Dumbo (CCS 2020)

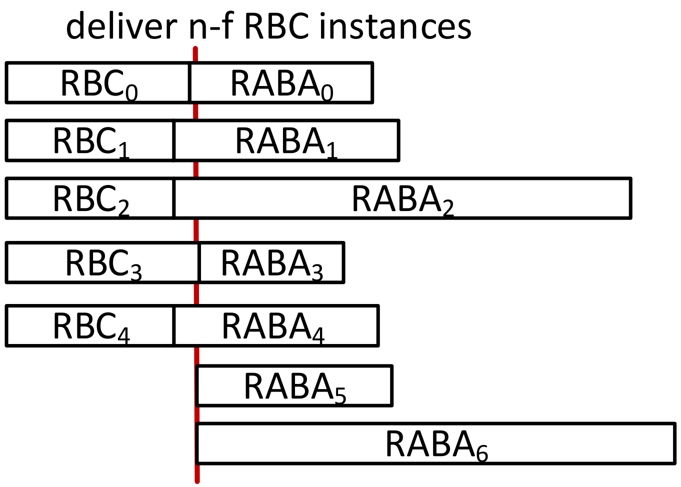
PACE (Zhang and Duan)



Significant performance gain compared to BKR

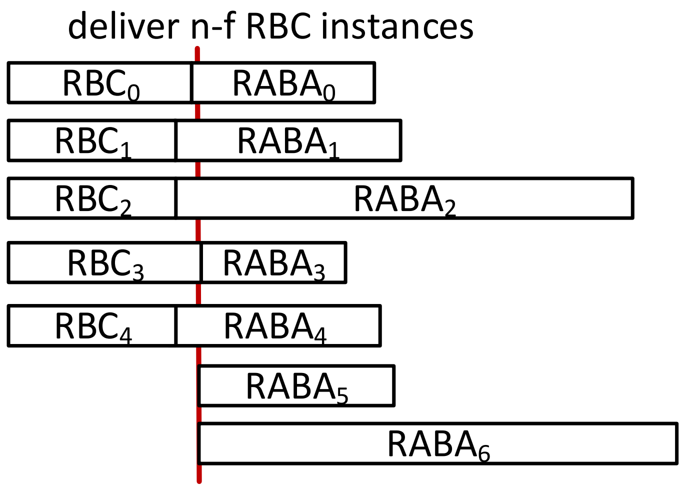
When f=30, the peak throughput of PACE-Pisa is **1.66x** that of Dumbo, **3.6x** that of BEAT (CCS 2018)

A Closer Look at PACE Paradigm



- **Challenges with RBC**
  - Bracha's broadcast (PODC 1984)
    - Information-theoretic
    - carry message payload in every step
    - $O(Ln^2)$ communication; not communication-efficient
    - WaterBear
  - CT RBC (SRDS 2015)
    - Quantum-secure
    - Uses hashes
    - $O(Ln+\kappa n^2 \log n)$ communication
    - WaterBear-QS
  - Can use recent advancement as well, e.g., EFBRB (PODC 2022), CCBRB (PODC 2022)

A Closer Look at PACE Paradigm



- **Challenges with ABA**
  - Most practical ABA rely on common coins
  - Instantiated with threshold signatures or threhsold PRF
- **Our solution**
  - Use ABA with local coins

ABA from Local Coins

```
Initialization
  r ← 0                                                  {round}
func propose(v)
  iv_0 ← v
  vset ← {0,1}           {valid binary values that will be accepted}
  start round 0
round r
  r-broadcast pre-vote_r(iv_r)                         {▷ phase 1}
  upon r-delivering n − f pre-vote_r() such that for each
pre-vote_r(v), v ∈ vset                                {▷ phase 2}
    if there are n − f pre-vote_r(v)
      decide v
      iv_{r+1} ← v
      vset ← {v}
    else
      v ← majority value in the set of pre-vote_r() messages
    r-broadcast main-vote_r(v)
  upon r-delivering n − f main-vote_r() such that for each
main-vote_r(v), v ∈ vset                               {▷ phase 3}
    if there are at least n/2 main-vote_r(v)
      vset ← {v}
    else
      v ← {⊥}
      vset ← {0,1}
    r-broadcast final-vote_r(v)
  upon r-delivering n − f final-vote_r() such that for each
final-vote_r(v), v ∈ vset; for each final-vote_r(∗), vset = {0,1}
    if there are at least 2f + 1 final-vote_r(v)
      decide v
      iv_{r+1} ← v
      vset ← {v}
    else if there are f + 1 final-vote_r(v)
      iv_{r+1} ← v
      vset ← {0,1}
    else
      c ← Random()                              {obtain local coin}
      iv_{r+1} ← c
      vset ← {0,1}
  r ← r+1
```

Figure 10: The Bracha's ABA protocol [13]. The code for p_i.

- **The only known ABA from local coins**
  - Bracha's ABA (PODC 1984)
  - 3 phases of n parallel RBC instances
  - $O(n^3)$ message
  - $O(2^n)$ time complexity due to the use of local coins
- **Our goals**
  - Design more efficient local coin based ABA
  - Avoid querying coins as much as possible
  - Coin-free fast path

Our Local Coin Based ABA

Bracha's ABA
$O(n^3)$ message
9 steps in the fast path

Cubic-ABA
$O(n^3)$ message
5 steps in the fast path

Quadratic-ABA
$O(n^2)$ message
4 steps in the fast path

ABA (local coins)	messages/round	steps/round
Bracha's ABA [14]	n^3	9 to 12
Cubic-ABA (this work)	n^3	5 to 7
Quadratic-ABA (this work)	n^2	4 or 5

Table 3: Local coin based ABA protocols with optimal resilience. We consider the messages and steps in each round. Messages/round and steps/round denote number of messages and steps among all replicas per round.

Our ABAs

- By replacing local coins with **weak common coins** or **comon coins**, we obtain more efficient ABA protocols compared to existing state-of-the-art ABA

ABA (weak common coins)	steps/round	rounds
MMR15 [57, 2nd alg]	9 to 13	$d+1$
Crain [26, 1st alg]	5 to 7	$d+1$
CC-ABA (this work)	4 or 5	$d+1$

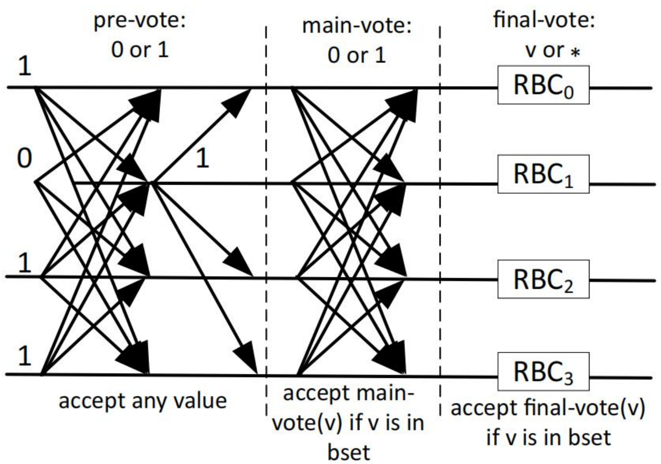
Table 4: ABA protocols using weak common coins. Rounds denote the expected number of rounds. The total number of steps is a product of steps/round and rounds.

ABA (common coins)	steps/round	rounds	good-case-coin-free
MMR15 [57, 2nd alg]	9 to 13	3	yes
Cobalt [53]	3 or 4	4	no
Crain [26, 1st alg]	5 to 7	3	yes
Crain [26, 2nd alg]	2 or 3†	4	no
Pillar [64]	2 or 3	4	no
CC-ABA (this work)	4 or 5	3	yes

Table 5: ABA protocols using perfect common coins. †The second algorithm of Crain relies high threshold common coins and is less efficient than Pillar. Compared to Pillar, CC-ABA has the good-case-coin-free property that is vital for the asynchronous distributed key generation protocol [30].

Our ABAs

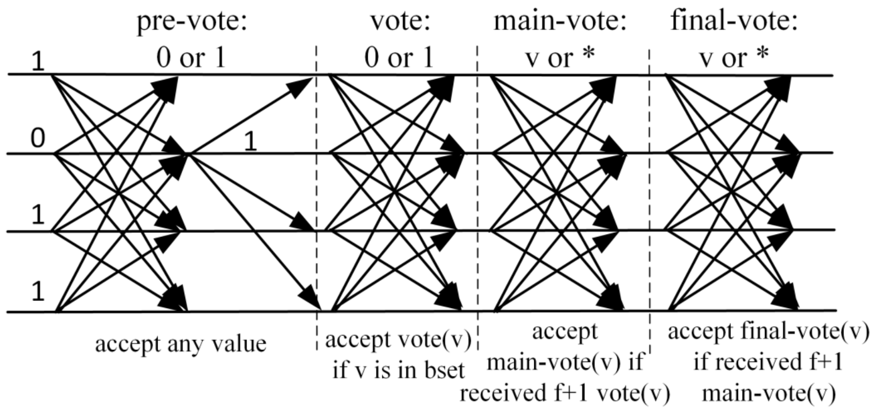
Cubic-ABA



Idea: Use all-to-all communication to replace parallel RBC as much as possible

Bracha's ABA involves 3 phases of n parallel RBC

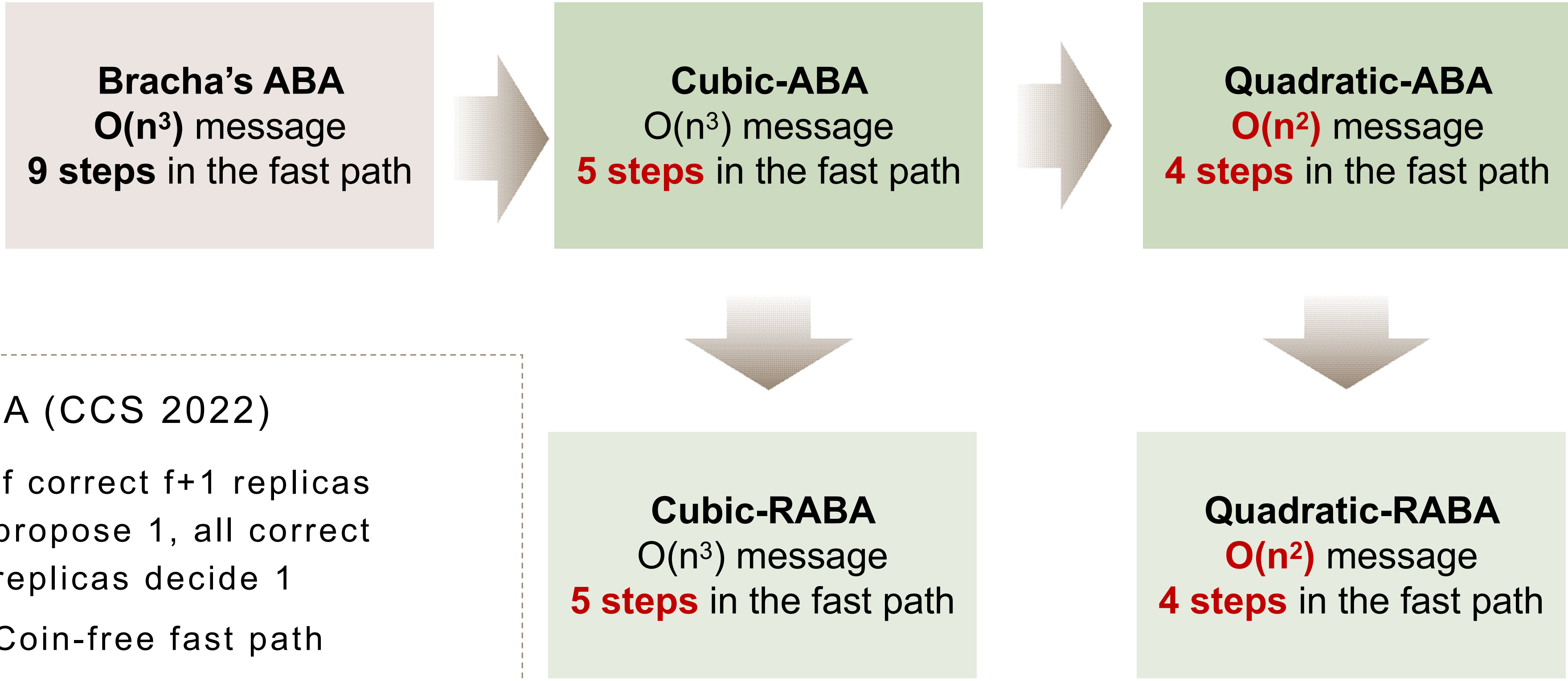
Quadratic-ABA



Idea: Use all-to-all communication only

Any voted value needs to be 'confirmed' by counting the number of votes from the previous step

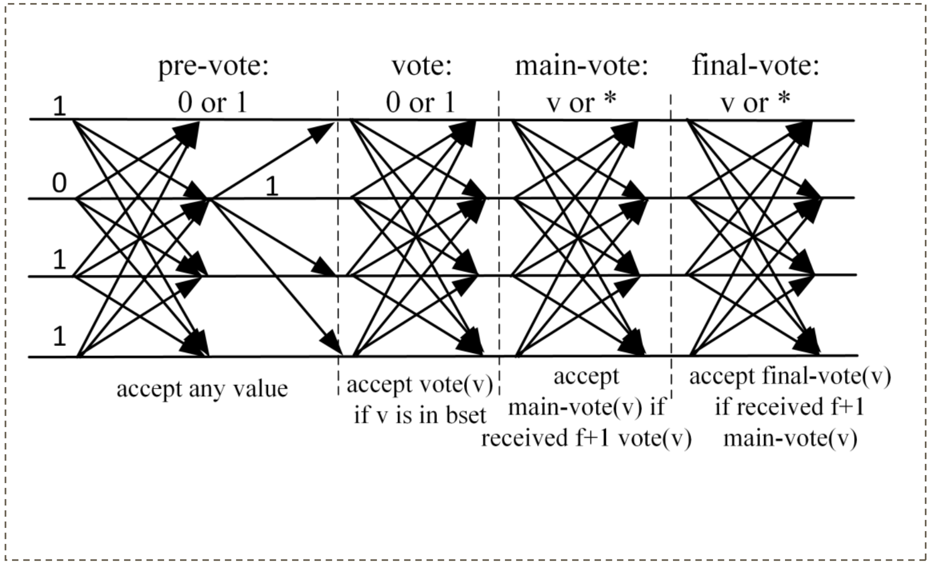
Local Coin Based RABA



- RABA (CCS 2022)
    - if correct f+1 replicas propose 1, all correct replicas decide 1
    - Coin-free fast path

Our RABA

Quadratic-RABA



Idea: Use all-to-all communication only

Any voted value needs to be 'confirmed' by counting the number of votes from the previous step

```
initialization
  r ← 0                                                        {round}
func propose(v)
  broadcast-vote(v)
  start round 0
func repropose(v)
  broadcast-vote(v)
func broadcast-vote(v)
  if pre-vote_0(v) has not been sent, broadcast pre-vote_0(v)
  if v = 1
    bset_0 ← bset_0 ∪ {1}
    if vote_0() has not been sent, broadcast vote_0(1)
    if main-vote_0() has not been sent, broadcast main-vote_0(1)
    if final-vote_0() has not been sent, broadcast final-vote_0(1)
round r
  if r > 0, broadcast pre-vote_r(iv_r)
  upon receiving pre-vote_r(v) from f+1 replicas
    if pre-vote_r(v) has not been sent, broadcast pre-vote_r(v)
  upon receiving pre-vote_r(v) from 2f+1 replicas
    bset_r ← bset_r ∪ {v}
  wait until bset_r ≠ ∅
    if vote_r() has not been sent
      broadcast vote_r(v) where v ∈ bset_r
   upon receiving n − f vote_r() such that for each received
vote_r(b), b ∈ bset_r
    if there are n − f vote_r(v)
      broadcast main-vote_r(v)
    else broadcast main-vote_r(∗)
   upon receiving n − f main-vote_r() such that for each
main-vote_r(v): 1) if r = 0, v ∈ bset_r, 2) if r > 0, at least f+1 vote_r(v)
have been received; for each main-vote_r(∗), bset_r = {0,1}
    if there there are n − f main-vote_r(v)
      broadcast final-vote_r(v)
    else broadcast final-vote_r(∗)
   upon receiving n − f final-vote_r() such that for each
final-vote_r(v), 1) if r = 0, v ∈ bset_r, 2) at least f+1 main-vote_r(v)
have been received; for each final-vote_r(∗), bset_r = {0,1}
    if there there are n − f final-vote_r(v)
      iv_{r+1} ← v, decide v
    else if there are only final-vote_r(v) and final-vote_r(∗)
      iv_{r+1} ← v
    else
      if r = 0, c ← 1                         {coin in the first round is 1}
      else c ← Random()                       {obtain local coin}
      iv_{r+1} ← c
  r ← r+1
```

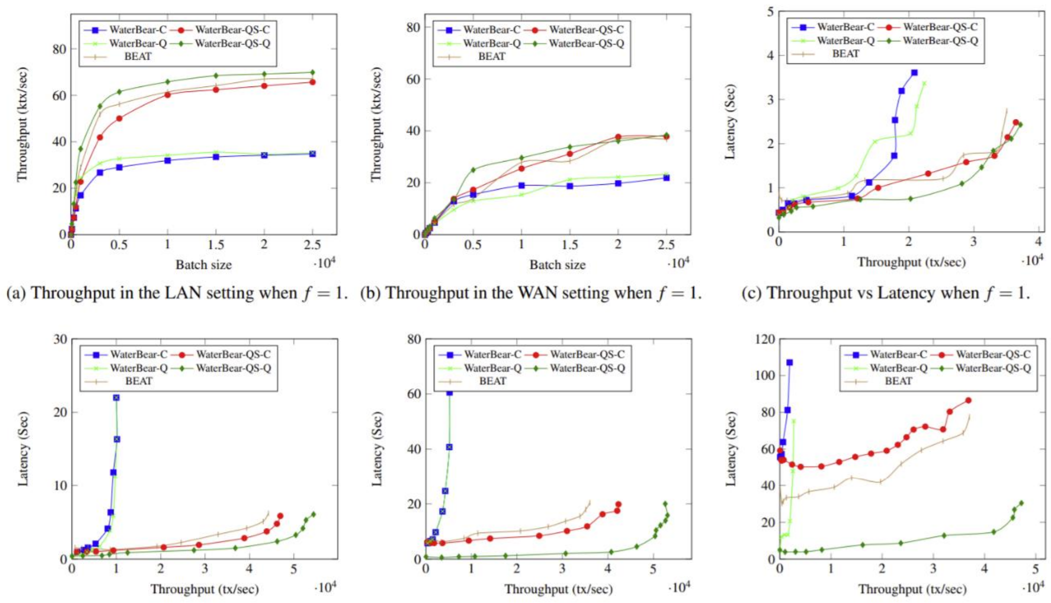
Evaluation

protocol	reference implementation	RBC	RABA	authenticated channels
WaterBear	WaterBear-C	Bracha's RBC [14]	Cubic-RABA (this paper)	HMAC*
	WaterBear-Q	Bracha's RBC [14]	Quadratic-RABA (this paper)	HMAC*
WaterBear-QS	WaterBear-QS-C	CT RBC [18]	Cubic-RABA (this paper)	HMAC
	WaterBear-QS-Q	CT RBC [18]	Quadratic-RABA (this paper)	HMAC

- Golang
- Evaluated 5 protocols in total
  - 4 new ones (WaterBear family)
  - BEAT (CCS 2018)
- AWS m5.xlarge, 4 vCPU, 16GB memory
- up to 61 instances

Results

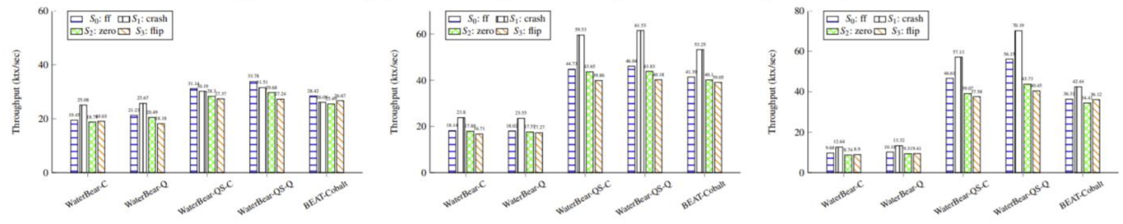
- All WaterBear-QS protcols outperform BEAT
  - n=16, WaterBear-QS-Q has 1/8 latency and 1.23x throughput compared to BEAT
  - Due to the use of PACE framework
- WaterBear-QS protocols consistently outperform WaterBear protocols
  - Communication is important!
- Building efficient quantum-secure asynchronous BFT is possible



(a) Throughput in the LAN setting when $f = 1$. (b) Throughput in the WAN setting when $f = 1$. (c) Throughput vs Latency when $f = 1$.

(d) Throughput vs Latency when $f = 5$. (e) Throughput vs Latency when $f = 10$. (f) Throughput vs Latency when $f = 20$.

Figure 8: Throughput vs latency on m5.xlarge instances for $f = 1$ to $f = 20$.



(a) Throughput for $f = 1$. (b) Throughput for $f = 2$. (c) Throughput for $f = 5$.

Figure 9: Performance of the protocols in failure scenarios.

WaterBear: Asynchronous BFT with Information-Theoretic Security and Quantum Security

Haibin Zhang, Sisi Duan, Boxin Zhao, Liehuang Zhu

- **Quadratic-ABA and Cubic-ABA:** Efficient local-coin based asynchronous binary agreement (ABA) protocols
- **WaterBear Family:** Efficient asynchronous Byzantine fault-tolerant (BFT) protocols with stronger security guarantees

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