Design and Deployment of COCA

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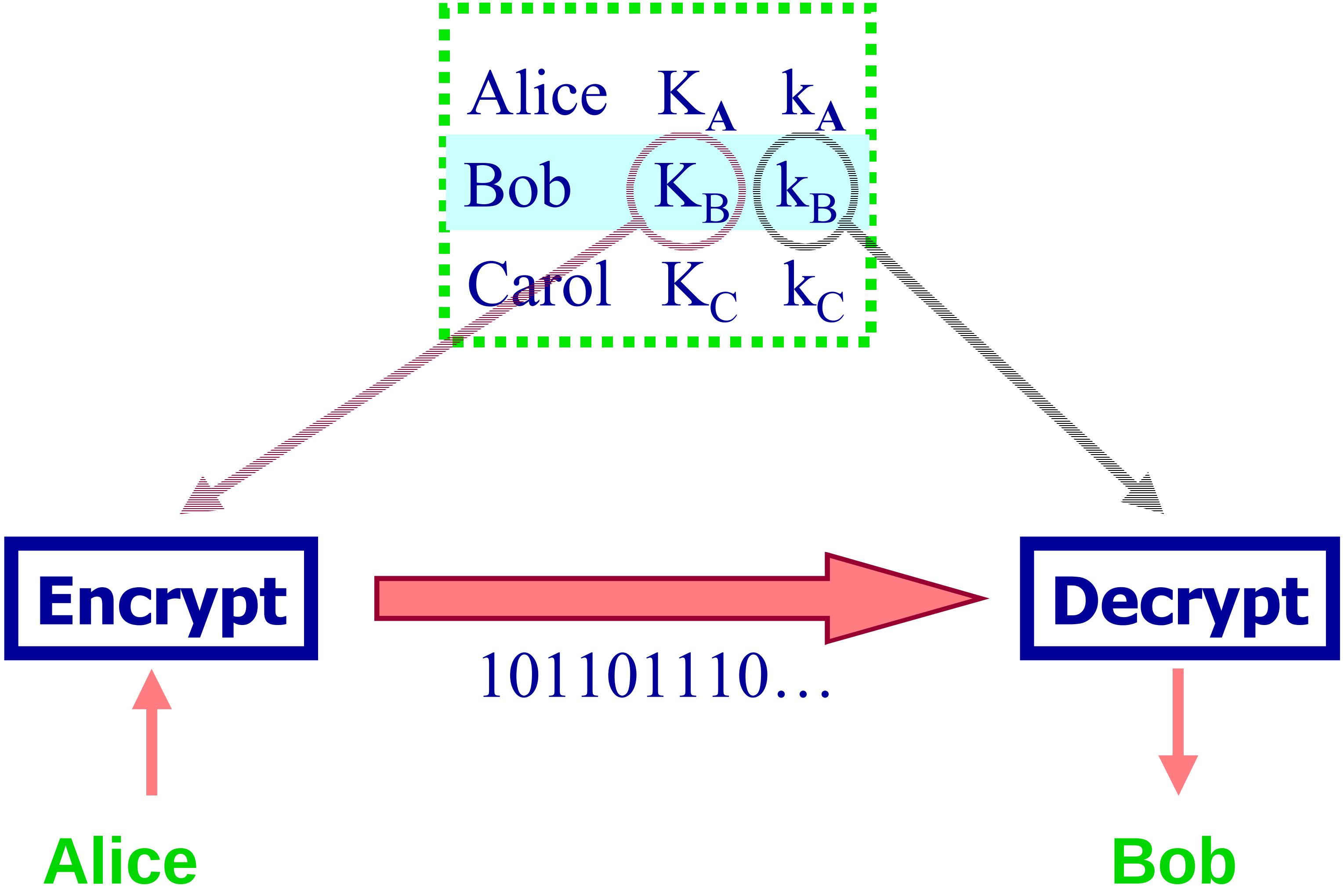
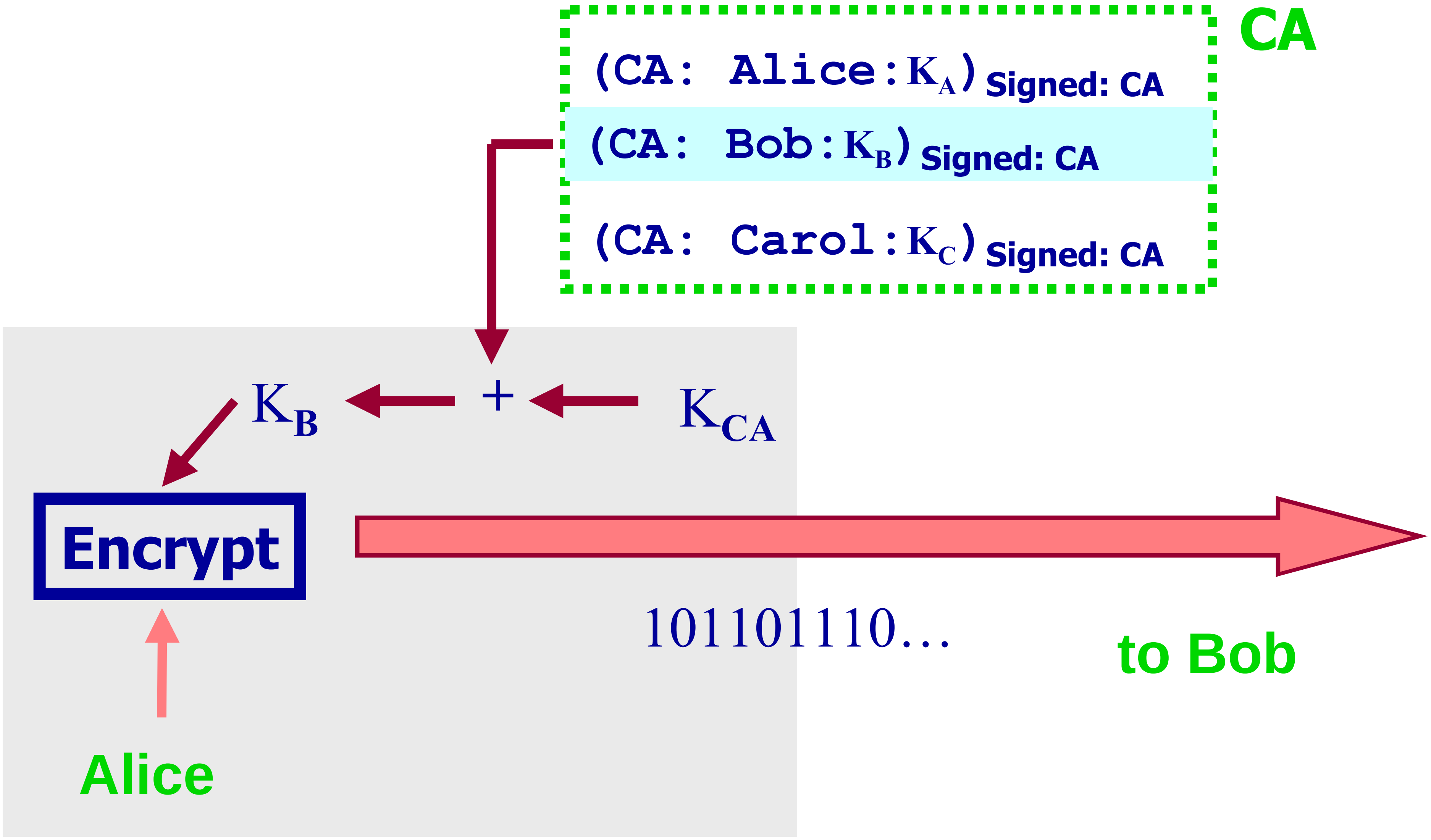
Public Key Cryptography



Alice	K_A	k_A
Bob	K_B	k_B
Carol	K_C	k_C

Using a Certification Authority



CA

(CA: Alice:K_A) Signed: CA

(CA: Bob:K_B) Signed: CA

(CA: Carol:K_C) Signed: CA

K_B ← + ← K_{CA}

Encrypt

101101110…

to Bob

Alice

Certification Authority

- CA stores certificates.
  - Each certificate is a binding: _name, K_{name}_
  - Each certificate is signed by CA.
- Clients know public key of CA. Clients issue requests:
  - Query to retrieve certificate for a name.
  - Update to change binding and invalidate certificate.

CA Security and Fault-tolerance

Fault-tolerance and security for a CA means

- CA service remains available.
- CA signing key remains secret.

despite

- failures (=independent events) and
- attacks (=correlated events).

COCA (Non)-Assumptions

- **Servers**: correct or compromised. At most t servers compromised during window of vulnerability, and $3t < n$ holds.
- **Fair Links**: A message sent enough times will be delivered.
- **Asynchrony**: No bound on message delivery delay or server speed.

Weaker assumptions are better.

Security and Fault-tolerance: Query and Update

Dissemination Byzantine Quorum System:

- Intersection of any two quorums contains at least one correct server.
- A quorum comprising only correct servers always exists.

- Replicate certificates at servers.
- Each client request processed by all correct servers in some quorum.
- Use service (not server) signing key.

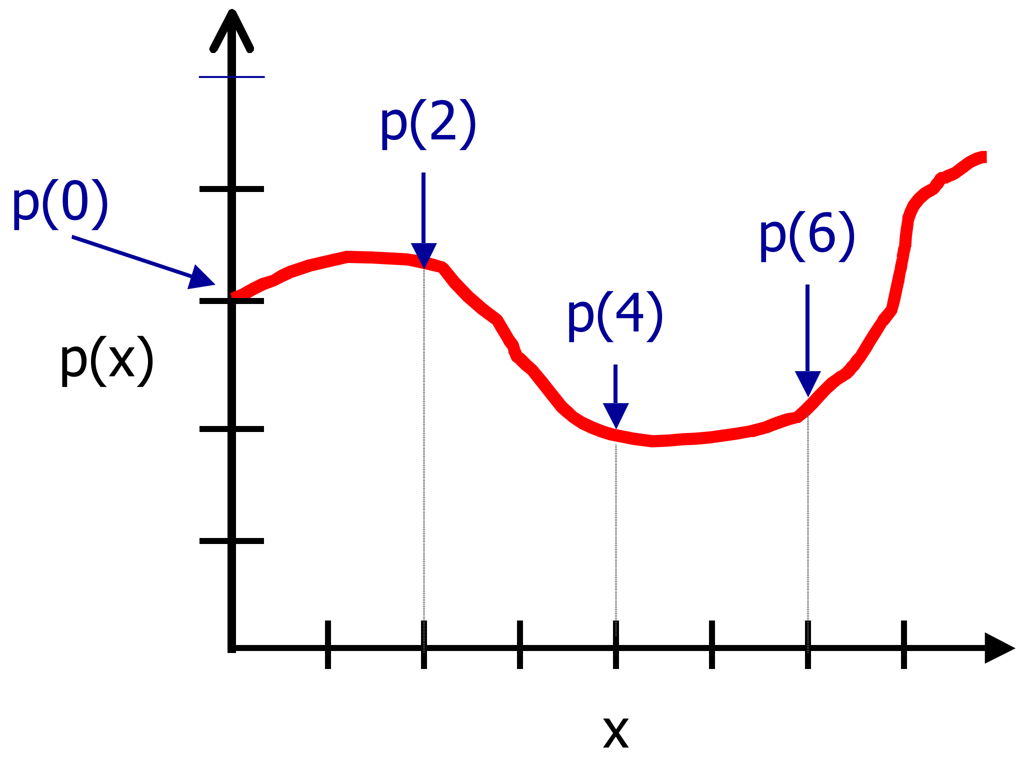
Security and Fault-tolerance:
Service Signing Key Secrecy

- Service signing key stored at each server.

versus

- Employ threshold signature protocol:
  - Store a <u>share</u> of signing key at each server.
  - Use (n, t+1) threshold cryptography to sign.

Security and Fault-tolerance: Secret Sharing



p(0) is secret

p(i) is share at site i

m points determine an m-1 degree poly

(n,k) secret sharing: k-1 degree poly

Security and Fault-tolerance: Mobile Virus Attacks

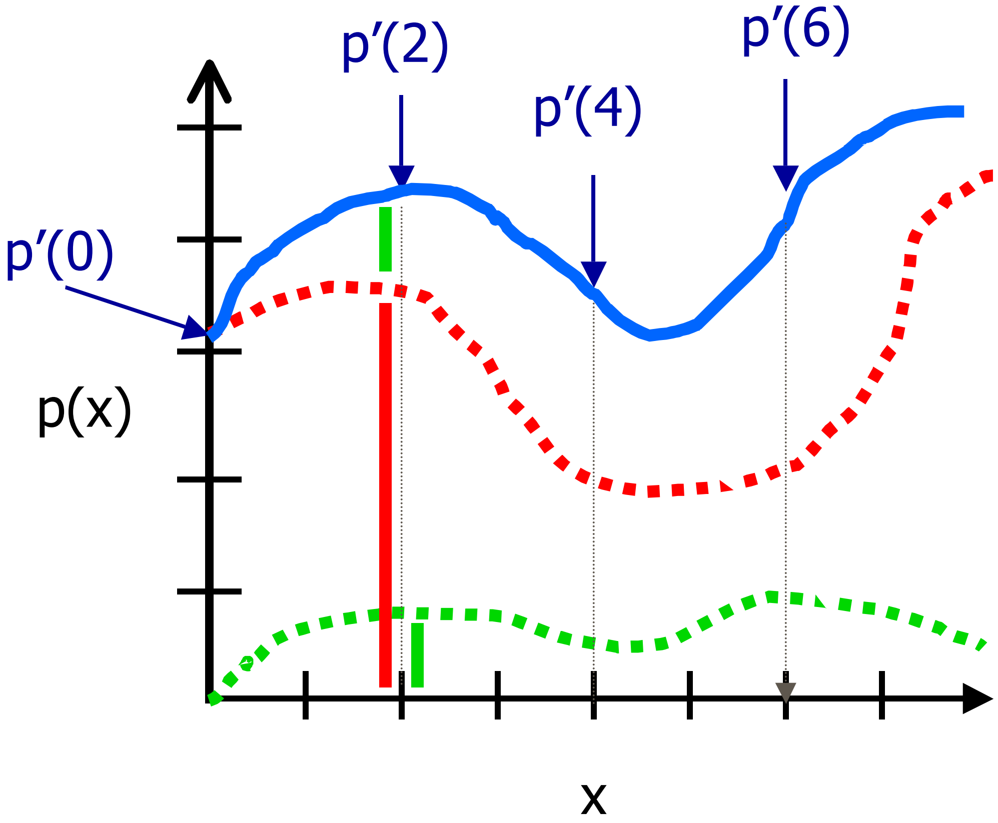
- Compromise server CA_1, detect, repair.
- Compromise server CA_2, detect, repair.

…

- Compromise server CA_{t+1}, detect, repair.

t+1 secret shares revealed, even though at most 1 site ever compromised.

Security and Fault-tolerance—Mobile Virus Attacks: Proactive Secret Sharing



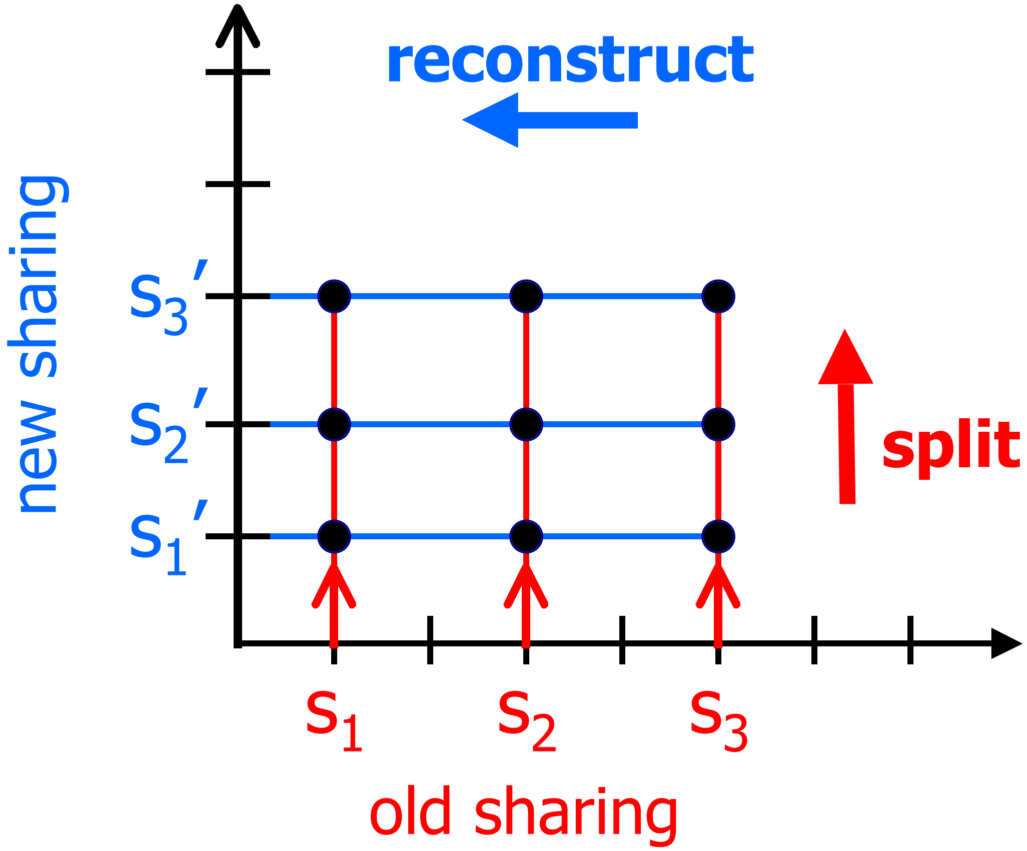
q(x): random poly

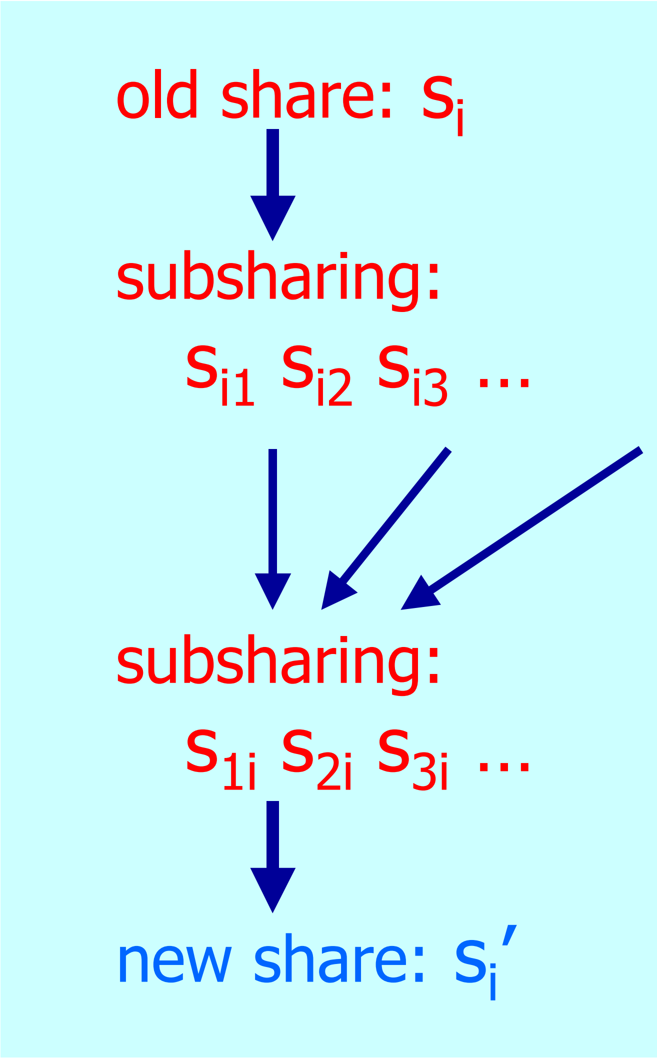
p′(x): p(x)+q(x)

p′(0) = p(0)

p′(i) is share at site i

Proactive Secret Sharing:
Computing New Shares





old share: s_i

subsharing:

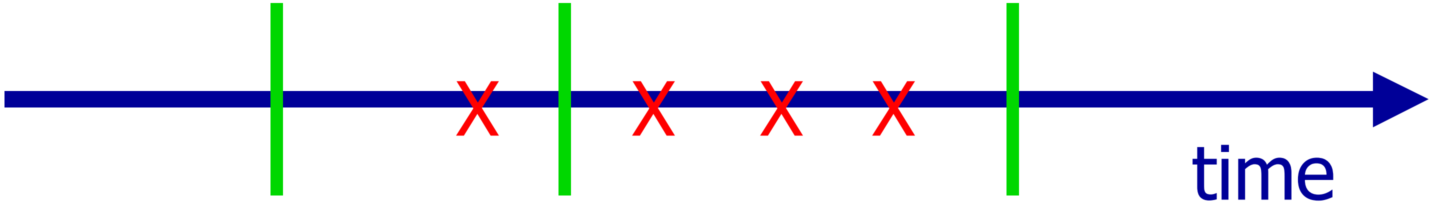
s_{i1} s_{i2} s_{i3} …

subsharing:

s_{1i} s_{2i} s_{3i} …

new share: s_i'

Proactive Secret Sharing:
Windows of Vulnerability



| proactive refresh

x server compromise

- At most t servers compromised in a window.
- Shares, keys, state all refreshed.
- Local clock at some server initiates refresh.
- Denial of service increases window size.

COCA Request Processing

- Client issues request and awaits response.
- COCA accepts request:
  - Some correct COCA server received request.
- COCA completes request:
  - Some correct COCA server constructs response.

Liveness: Every accepted request eventually is completed.

COCA Request Processing: Ordering Client Requests

- Query collects multiple certificates from servers.
- Select one based on serial number.
- Update is not indivisible:
  - invalidate / create certificate are **separate** actions
  - Consequences:
    - Assign serial numbers consistent with service-centric causality relation **Å**.
    - C_1 **Å** C_2: C_2 created by Update having input C_1
    - Certificate—not just name—is input to Update.

Key Management in COCA

- Service public key known to clients.
- Service private key is shared among servers.
  - Private key shares refreshed periodically.
  - Server state also refreshed.

- Server public keys not known to clients.
  - Changing server keys possible, despite large numbers of clients.
  - Clients cannot authenticate server responses.

Role of Delegates

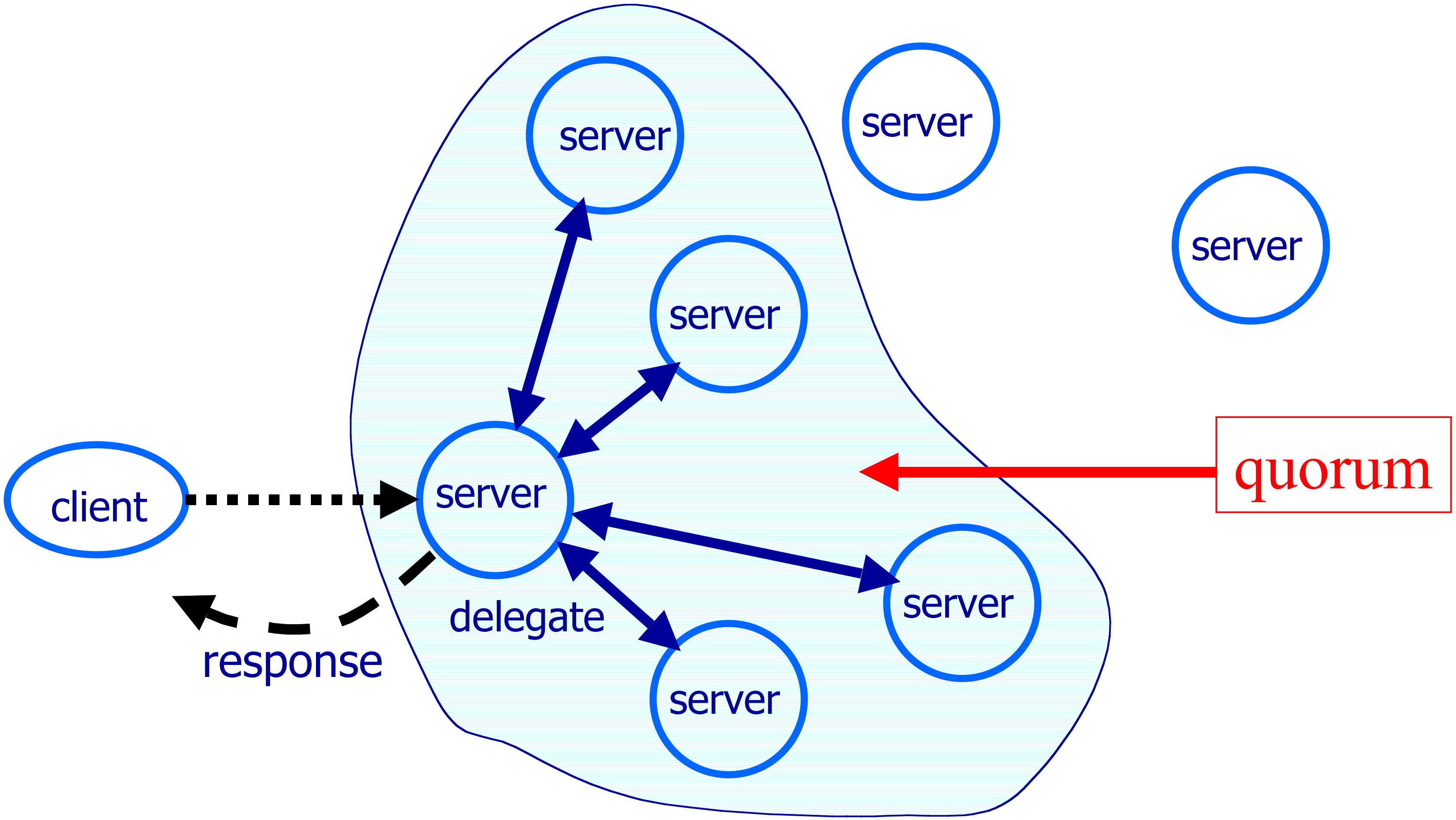
Problem: Without server public keys …

- Clients cannot authenticate messages from servers.
- Clients cannot determine whether a request has been processed by a quorum.

Solution: Delegate collects responses.

- Client requests are signed and include nonce.
- Delegate handles request on behalf of client. It is a server and it knows COCA public keys.

COCA Architecture



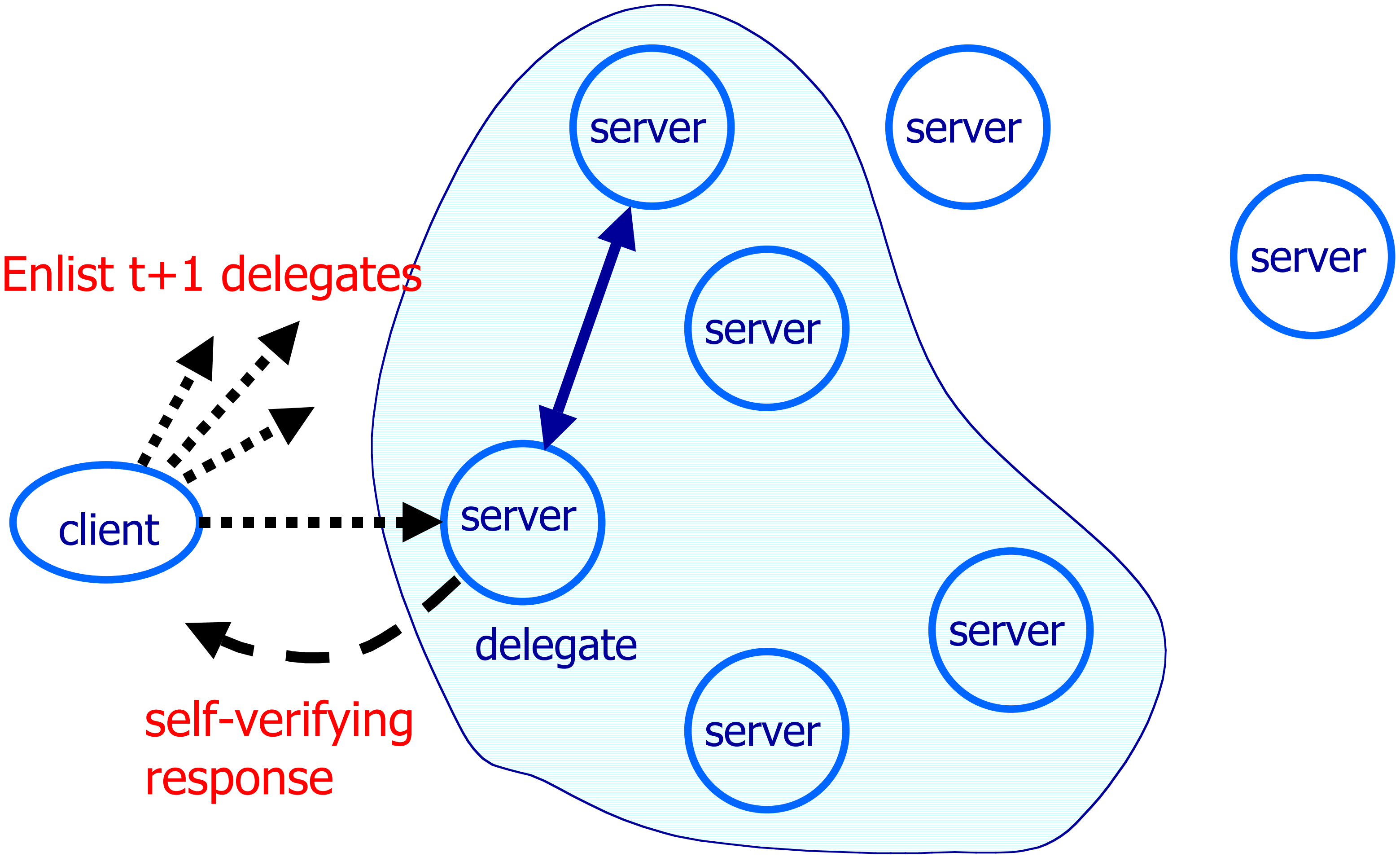
Processing a Query Request Q

- Delegate forwards Q to all COCA servers.
- Delegate awaits certs from a quorum.
- Delegate selects cert with largest serial number.
- Delegate runs threshold protocol to sign response with nonce and cert.
- Delegate sends response to client.

Processing an Update Request U

- Delegate constructs new certificate c, using threshold protocol to generate signature.
- Delegate sends c to all COCA servers.
- Upon receipt, server replaces current certificate for that name iff c has larger serial number. Server then sends “done” to delegate.
- Delegate awaits “done” from a quorum of servers.
- Delegate runs threshold protocol to sign response with nonce and cert.
- Delegate sends response to client.

Compromised Delegate

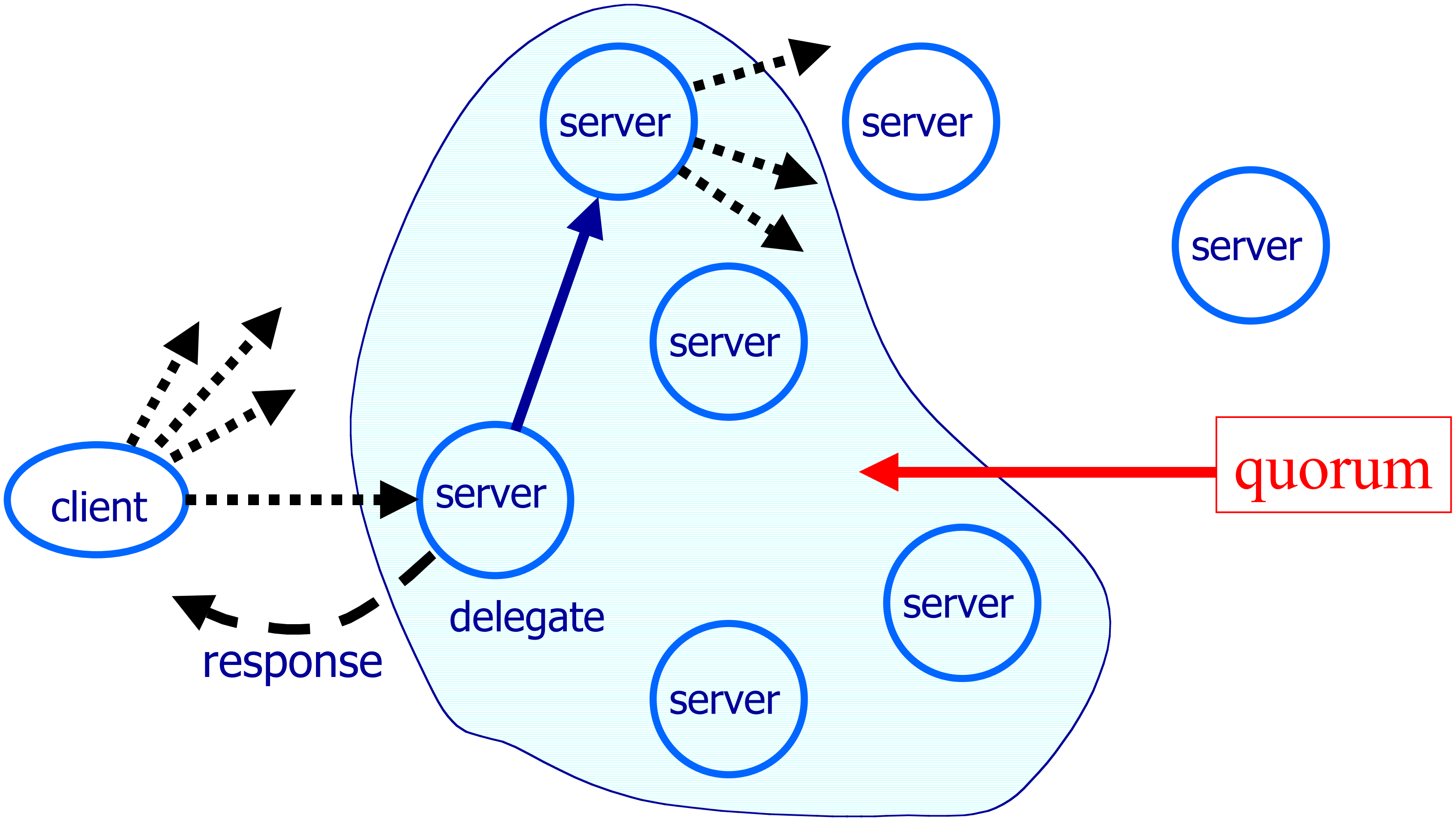


Self-verifying Messages

A self-verifying message comprises:

- Information the sender intends to convey.
- Evidence the receiver can check that the information is consistent with given protocol.

Compromised Client



Message Loss due to Fair Links

Defense against message loss …

- Resend each message until ack received from intended recipient.

Defense against compromised recipient …

- Protocol structured as a series of multicasts.
  - If ack received from enough recipients, halt resending.
  - Ensure there are enough correct recipients even if t servers are compromised.

Denial of Service Defenses

Problem: Denial of service possible if cost of processing a bogus request is high.

Defenses:

- Increase cost of making a bogus request.
- Decrease cost/impact of processing a bogus request.
  - Cheap authorization mechanism rejects some bogus requests.
  - Processor scheduler partitions requests into classes.
  - Results of expensive cryptographic operations cached and reused
- Asynchrony and Fair Links non-assumptions.

Experimental COCA Deployments

Prototype implementation:

- Approx. 35K lines of new C source
- Uses threshold RSA with 1024 bit RSA keys built from OpenSSL
- Certificates in accordance with X.509.

Deployments:

- Cornell CS Dept local area network
- Internet:
  - University of Tromso (northern Norway)
  - University of California (San Diego, California)
  - Dartmouth College (Hanover, New Hampshire)
  - Cornell University (Ithaca, New York)

Engineered for Performance

In the normal case:

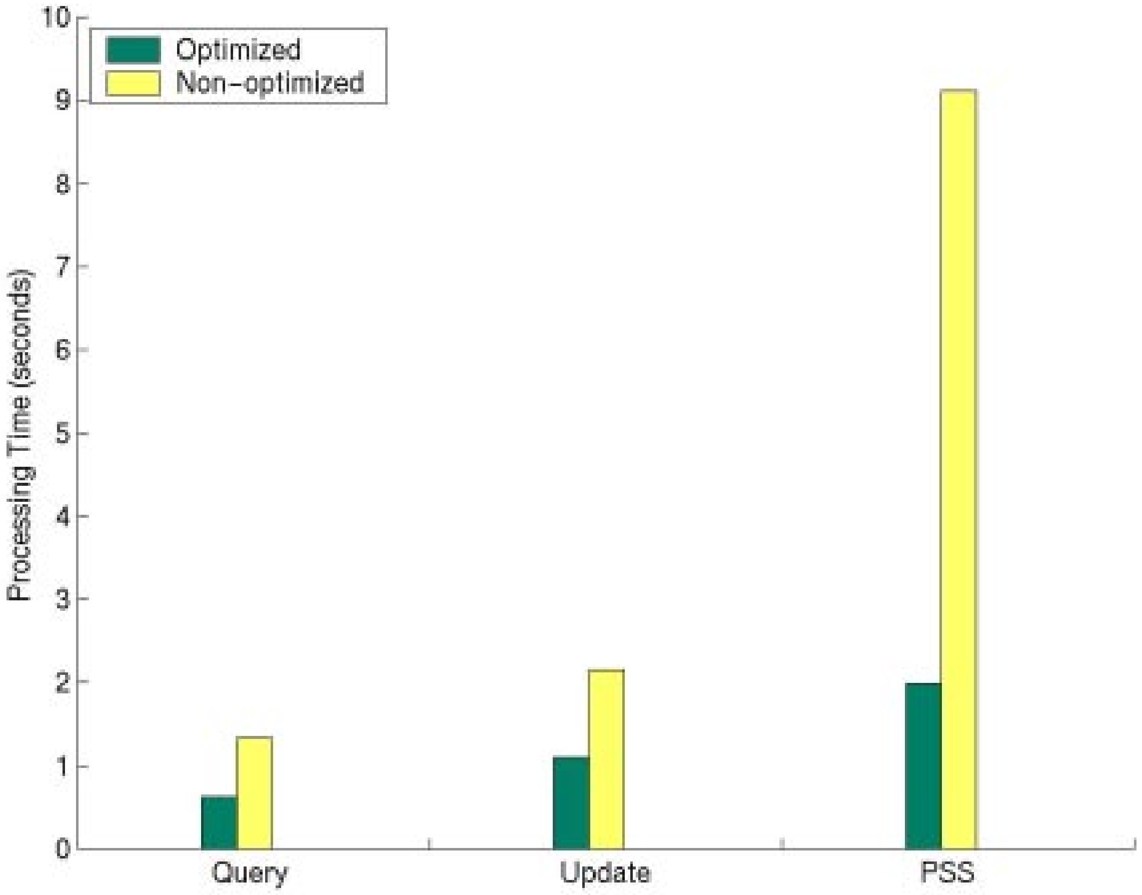
- Servers satisfy strong assumptions about execution speed.
- Messages sent will be delivered in a timely way.

COCA optimizes for the normal case.

“Normal Case” Optimizations

- Client enlists a single delegate. Only after timeout are t additional delegates contacted.
- Servers do not become delegates until client asks or timeout elapses.
- Delegates send responses to client and to all servers. Used to abort activity and load the cache.

“Normal Case” Optimizations



LAN Performance Data

COCA Operation	**Mean** *(msec)*	**Std dev.** *(msec)*
Query	629	16.7
Update	1109	9.0
PSS	1990	54.6

4 Sun E420R SPARC servers (4 450 Mhz processors. Solaris 2.6)

100 Mb Ethernet (Round trip delay for UDP packet: 300 micro secs)

Sample means for 100 executions.

LAN Performance Breakdown

	Query	Update	PSS
Partial Signature	64%	73%	
Message Signing	24%	19%	22%
One-Way Function			51%
SSL			10%
Idle	7%	2%	15%
Other	5%	6%	2%

WAN Performance Data

COCA Operation	**Mean** *(msec)*	**Std dev.** *(msec)*
Query	2270	340
Update	3710	440
PSS	5200	620

WAN Performance Breakdown

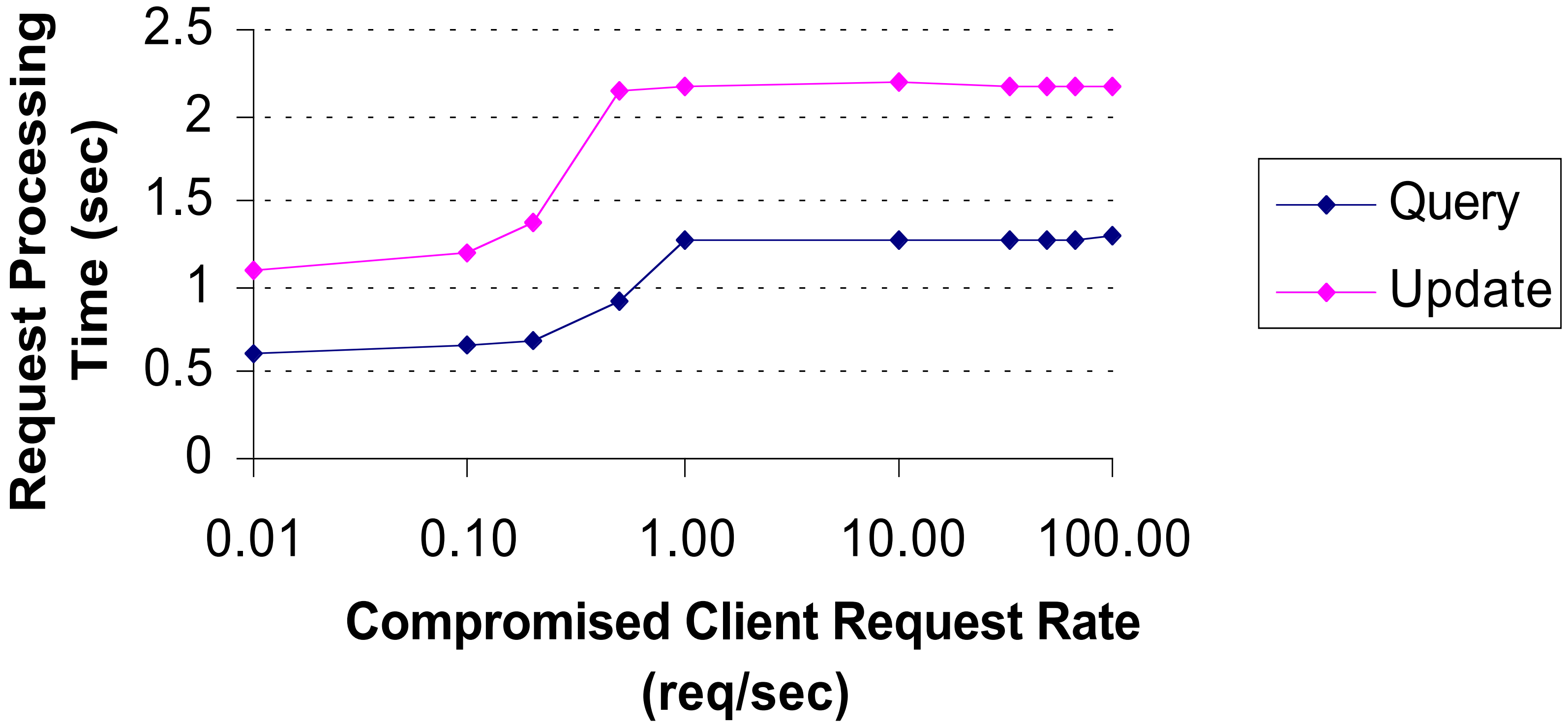
	Query	Update	PSS
Partial Signature	8.0%	8.7%	
Message Signing	3.2%	2.5%	2.6%
One-Way Function			7.8%
SSL			1.6%
Idle	88%	88.7%	87.4%
Other	0.8%	1.1%	0.6%

Denial of Service Attacks

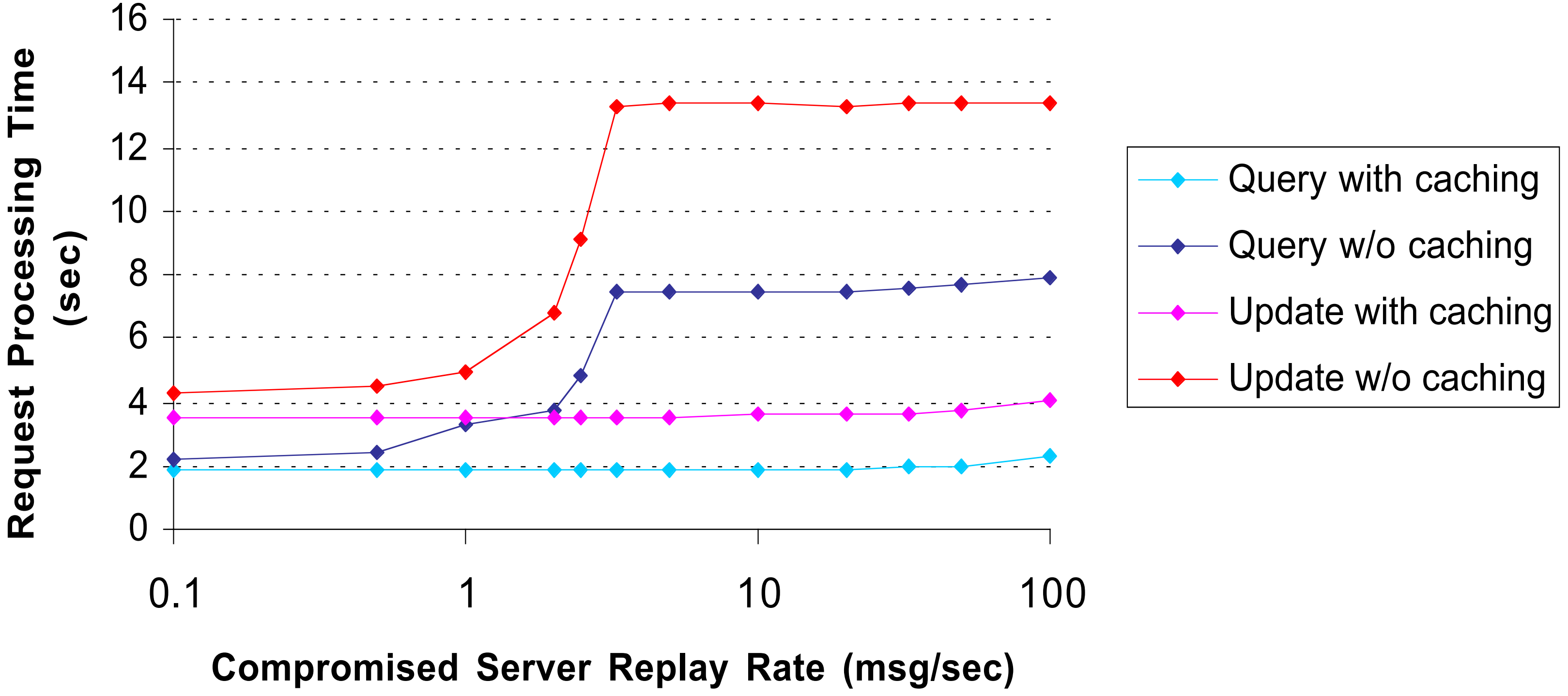
Attacker might:

- Send new requests.
- Replay old client requests and server messages.
- Delay message delivery or processing.

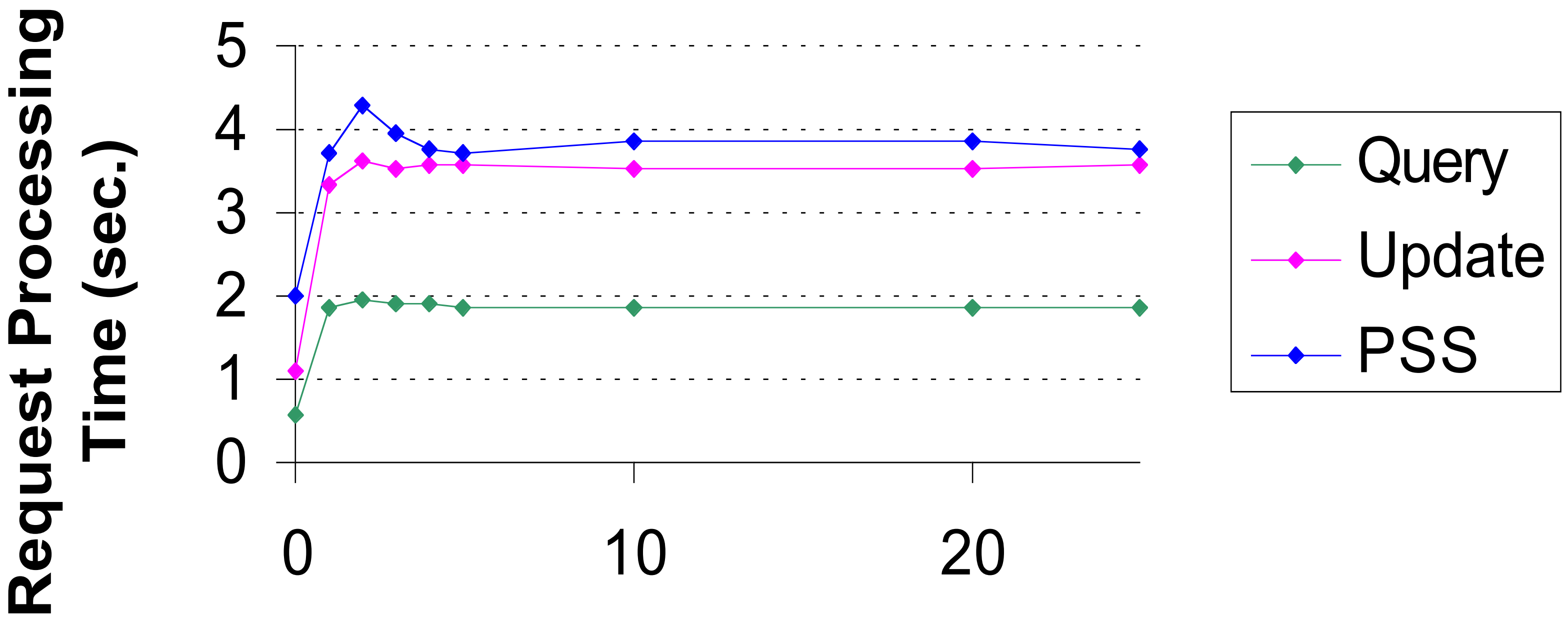
Denial of Service Defense:
Scheduler-Enforced Isolation



Denial of Service Defense:
Effects of Caching

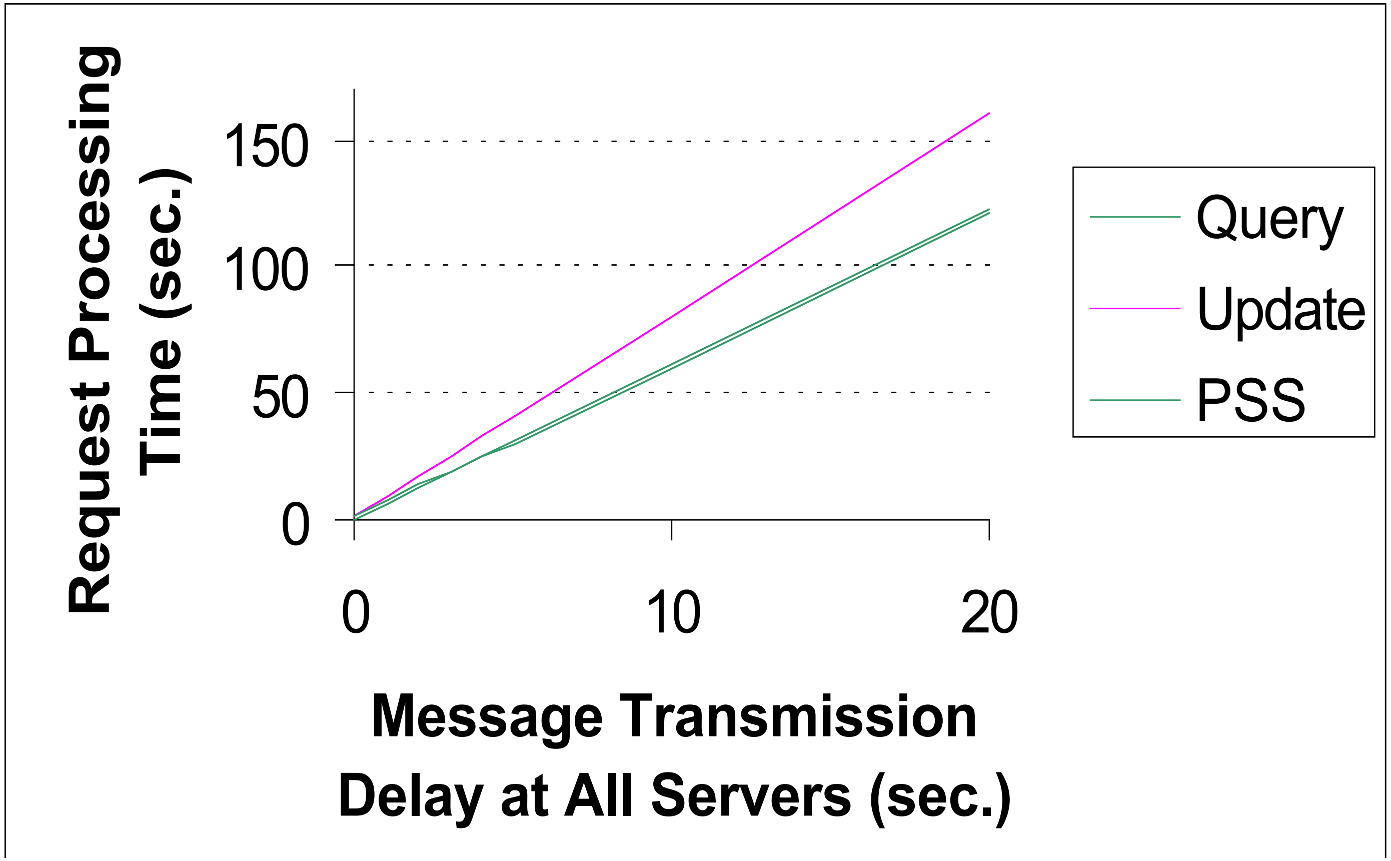


Denial of Service Defense:
Effects of Message Delay

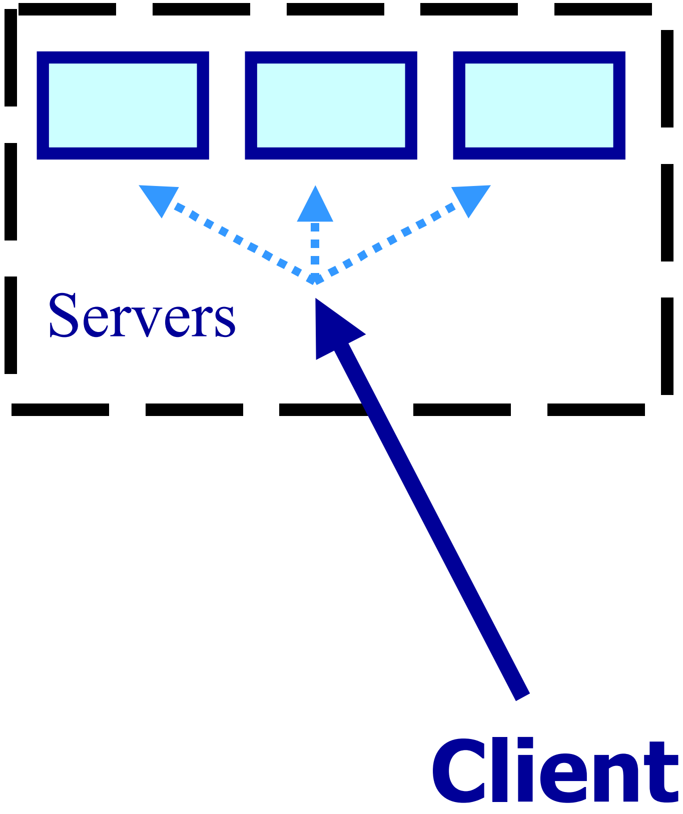


Message Transmission Delay at a Single Server (sec.)

Denial of Service Defense:
Effects of Message Delay



COCA: Recap of Big Picture



server failure

↓ dissem. Byzantine Quorum

server compromise

↓ threshold signature protocol

mobile attack

↓ proactive secret sharing (PSS)

asynchrony

↓ asynchronous PSS