A BFT KV Storage

Yahoo Paranoids
https://github.com/yahoo/bftkv

Introduction

We design a distributed BFT key-value storage based on Byzantine quorum systems[1]. The system consists of:

- Phalanx[2] -- a BFT protocol designed by the same authors who introduced Byzantine quorum systems. We use the protocol for the underlying READ/WRITE operations.
- Web of Trust -- to construct a b-masking quorum system that satisfies the Byzantine quorum properties.
- Quorum certificate -- to prevent unauthorized mutation.

Unlike consensus protocols, the proposed system does not guarantee that all replica nodes have the same data. Instead, it has a property: $READ(Q_1, x) = READ(Q_2, x), \forall Q_1, Q_2 \in QS$. Consensus is established collectively. The key-value store is useful by itself but we also show how the property can be used to construct other distributed systems that need consensus among replicas.
Besides the above fundamental features, i.e., READ and WRITE with quorum systems, we design password based roaming protocols, which is immune to the offline dictionary attack even if some servers are compromised. The same mechanism and protocols are used for registration of new nodes users generate themselves.

Background

Quorum Systems

A variety of quorum systems have been used to manage replicated data / storage in distributed systems. We briefly describe the original quorum systems and its extension called Byzantine quorum systems. Later, we construct a byzantine quorum system based on Web of Trust.
The system defines two operations, READ and WRITE, between a client and a set of servers called a quorum. A quorum system ($QS \subseteq 2^U$) is a subset of the powerset of all servers (U), and it satisfies a property:

[1] D.Malhi, M.Reiter. "Byzantine Quorum Systems" [http://www.cs.utexas.edu/users/lorenzo/corsi/cs380d/papers/bquorum-dc.pdf]
[2] D.Malhi, M.Reiter. "Secure and Scalable Replication in Phalanx" [https://www.cs.unc.edu/~reiter/papers/1998/SRDS-1.pdf]

$\forall Q_1, Q_2 \in QS, \; Q_1 \cap Q_2 \neq 0$ (intersection)

The write operation is done between a client (c) and a quorum (Q), writing a value (v) to a variable (x):

Choose $Q \in QS$, and for each $q \in Q$ do: write(x, $<v, t>$)

The read operation is as follows:

1. Choose $Q \in QS$, and for each $q \in Q$ do: $<v, t>_q \leftarrow$ read(x)
2. Choose the pair that has the latest timestamp: $<v, t>$
3. Write the value back to Q: for each $q \in Q$ do: write(x, $<v, t>$)

Note Q can be chosen independently of the write operation. Because of the intersection property at least one server should have the right value.

The original quorum system handles only the benign failure (fail stop) case. Malkhi and Reiter [ref] extend the system so that it can deal with byzantine failure, calling it Byzantine quorum systems. With the signed message (SM) byzantine, the intersection property is extended as:

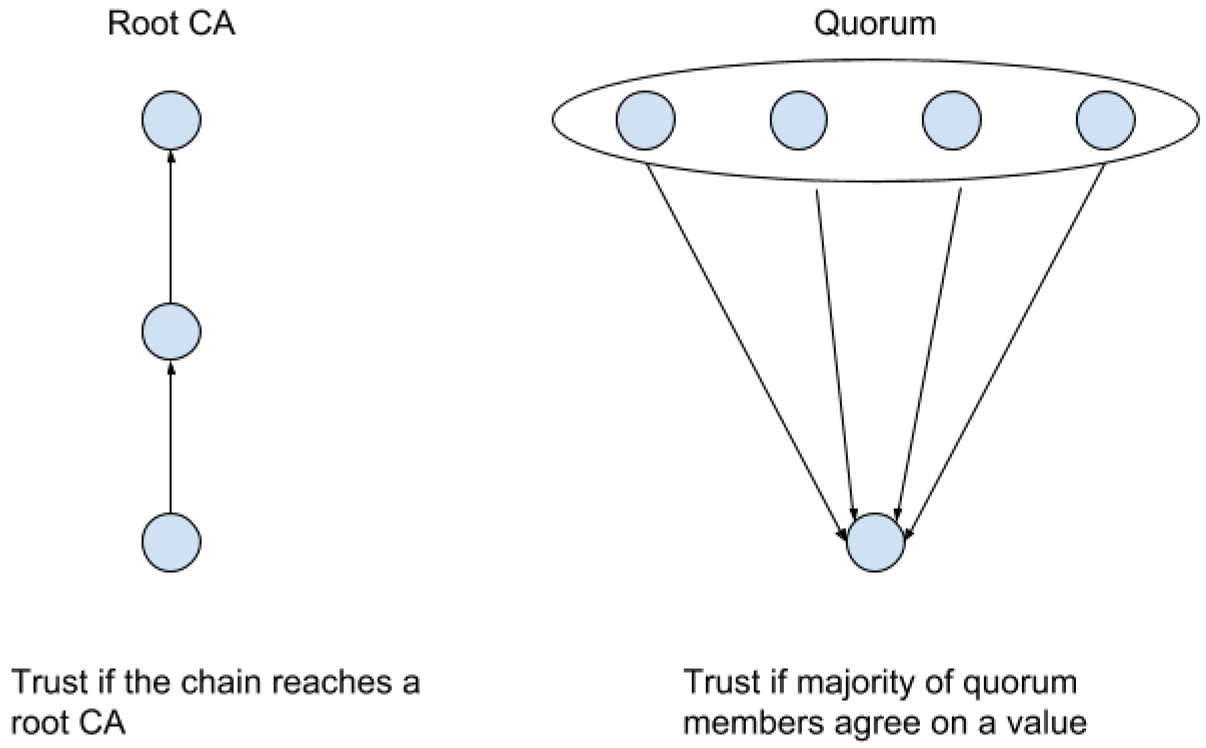
$\forall Q_1, Q_2 \in QS, \; \forall B \in BF : \; Q_1 \cap Q_2 \neg \subseteq B$

Where BF is a subset of the powerset of U and $\bigcup_{B \in BF} B$ is all byzantine failure nodes.

Quorum Certificate

Practical Byzantine Fault Tolerance system (Castro [ref]) uses a byzantine quorum system to order requests at each node to replicate data among them. A node, either client or server, writes a value to a quorum and if it collects at least $f+1$, where f is the maximum number of replicas that may be faulty, positive responses, the process is successful and the value is considered to be verified.

Quorum certificates are not a data structure such as X.509 but more like a protocol to certify a value stored in a quorum:


Root CA
Quorum
Trust if the chain reaches a root CA
Trust if majority of quorum members agree on a value

Web of Trust

A web of trust is a directed graph $G = (V, E)$, where V is a set of nodes (each of which is a pair of unique ID and public key) and E is a set of trust relationship: when $(v_1, v_2) \in E$, v_1 trusts v_2, i.e., the certificate of v_2 includes a signature over its public key with the private key of v_1. WoT was introduced by PGP [ref] to authenticate certificates of peers without relying on central authorities. We use the same mechanism to authenticate not only end-users' certificates but quorum members as well.

System Design

The system uses two quorum systems: one is to collect signatures, called authority(QS_A), and another one is to read/write key-value pairs (QS_B). The protocols do not depend on quorum systems -- any quorum system can plugged-in.

Abstract Protocols

$WRITE(x, v)$ requests to store a value v to a variable x.

[write]

```
    $C$    :    choose a quorum $Q \in QS_A,\ s.t.\ |Q| \geq 3b + 1$
```

```
$C \rightarrow Q$:    “get time”, with the variable $x$
$C \leftarrow Q$:    collect timestamps $\{t_1, t_2, ..., t_n\}, n \geq 2b+1$
$C$    :    $t \leftarrow max(t_i) + 1$
$C \rightarrow Q$:    “echo request”, $<x, t, v, sig>$ where $sig = Sign(Priv_C, <x, t, v>)$
$q_i \in Q$    :    check the signature with the $C$’s certificate
                verify $C$’s certificate with a quorum certificate
                check TOFU
                $s_i \leftarrow Sign(Priv_{q_i}, <x, t, v, sig>)$
$C \leftarrow Q$:    collect signatures $S = \{s_1, s_2, ..., s_m\}, m > b + (n-b)/2$
$C$    :    choose a quorum $Q' \in QS_B$
$C \rightarrow Q'$:    “write”, $<x, t, v, sig, S>$
$q_i \in Q'$:    verify $sig$
                check if the number of valid signature in $S$ is $> b + (n-b)/2$
                then check if $t$ has not been written into $x$
                store $<x, t, v, sig, S>$ into the storage
$C \leftarrow Q'$:    ack / nack
$C$    :    if the number of acks is $\geq 2f+1$ then success, otherwise fail
```

$READ(x)$ requests to retrieve the latest value of variable x.

```
[ read ]
    $C$    :    choose a quorum $Q \in QS_B$
    $C \rightarrow Q$:    “read”, $x$
    $C \leftarrow Q$:    collect key-value pairs $\{<x, t_i, v_i, sig_i, S_i>\}$ up to $2f+1$
    $C$    :    revoke all signers who have signed $<t, v>$ and $<t, v'>$
                discard pairs that do not have sufficient number of valid signatures
                choose a pair $<t, v>$ $s.t.\ \#(<t_i, v_i>) \geq b+1$ and has maximum timestamp
    [ write back (optional) ]
    $C$    :    $Q = \{$ all nodes that have not returned a pair $<x, t_i, v_i>$ $\}$
    $C \rightarrow Q'$:    “write back”, $<x, t_i, v_i, sig, S>$
    $q_i \in Q'$:    same as “write”
                // no response
```

- On “echo request”, we accept requests only when it is verified with a quorum certificate, i.e., $b+1$ members in a quorum must agree on the client’s certificate.
- We also enforce the TOFU policy, i.e., if a variable x already has a value, only when the client’s identity is the same as the previous one the new value will be accepted to get signed. Combined with the above check with quorum certificates, it can recover from the key-loss situation as long as the new key is signed by the same quorum.[3]

[3] See Appendix for the identity and key, for example.

- Q' can be larger than Q in the "write" protocol, which means a small set of signatures can be propagated to a large set of servers, therefore the burden of verifying signatures can be kept reasonable.
- On the "read" protocol, if the client finds $<x,t,v>$ and $<x,t,v'>$ with the same signer, either a client or a server, it must revoke the signer on the spot, and write back "a proof of malicious work" $(\{<x,t,v,sig,S>,\ <x,t,v',sig',S'>)$ to all servers.[4]
- Servers must keep all versions of values with timestamps.
- Servers can deny excessive write requests to mitigate a DoS type attack.
- The quorum system intentionally slows down the process of issuing new certificates.

Besides the above fundamental protocols, we have a couple of protocols to maintain the network configuration. Unlike above, these protocols are only between servers.

[join]

$s \rightarrow S$: $Cert_s$

s_i : add s to QS_B

$s \leftarrow S$: return peer nodes of s_i $<Cert_{s_1},\ Cert_{s_2},\ ...,\ Cert_{s_n}>$

[leave]

$s \rightarrow S$: $Cert_s$

s_i : remove s from QS_B

// no response

Each node constructs a trust graph independently from the self certificate and ones returned by the "join" protocol. A node may issue the join request to nodes that were not included in the initial request. It repeats until collecting the certificates from all nodes in the graph. It is possible to fail to get the certificate from some nodes because of network failures or system problems, and in that case each node could see different graph. Even in that case, as long as the failure nodes are less than the quorum threshold (see the "Quorum System" below) the system will work properly.

Note that all transactions are signed by sender, and verified by receivers before processing the request. Therefore, no entities can issue join / leave for anyone else.

Transport Security

Transport security between clients and quorum members cannot be provided by ordinary SSL as the system does not rely on central authorities. We sign all messages between clients and each quorum member using certificates assigned to quorum servers and clients[5]. Secrecy is not necessary in theory - only integrity has to be guaranteed so that signed message (SM)

[4] This kind of "write back" might be blocked by attackers if they have enough power to control the Internet traffic but as the client keeps the revocation list, it will never accept any kind of message from revoked nodes.

[5] PGP certificate in mind, which can have more than one signatures unlike X.509.

byzantine quorum systems work, but encrypting messages could help mitigate some attacks in practice, so we encrypt and sign all messages by default.

Quorum System

The quorum system consists of one or more cliques in the trust graph, each of which has at least $4b+1$ nodes. As long as one of cliques is reachable from clients the quorum system satisfies the intersection property. Each clique has to be maximal and any two cliques do not share any node. We call cliques that satisfy those conditions quorum cliques (QC):

$$Q = \bigcup_i QC_i,\ QC_i \cap QC_j = 0 \text{ for } \forall i,j$$

A QC can be b-masking quorum system and constructed with: $g(s,\bullet)$ with the start node s.

Algorithm

A function $g(s,\ L)$ that constructs all clique quorums that have distances less than L from s :

```
1. $V_s \leftarrow \{\},\ queue \leftarrow \{(s,0)\}$
2. repeat until $queue = \{\}$
    a. $(v,d) \leftarrow dequeue$
    b. if $d \geq L$ break
    c. $QC_i \leftarrow$findMaximalClique($v$)
    d. for each edge $e$ of $v$
        i. $queue \leftarrow (e.v,\ d+1)$ if it has not been visited
3. return $\{QC_i\}$
```

findMaximalClique(s):

```
1. $C \leftarrow \{s\}$
2. for each $v \in V$
    a. $C = C + \{v\}$ if both $(c_i, v)$ and $(v, c_i) \in E$ for $\forall c_i \in C$
3. check that any $c_i \in C$ does not have a clique other than $C$
4. return $C$
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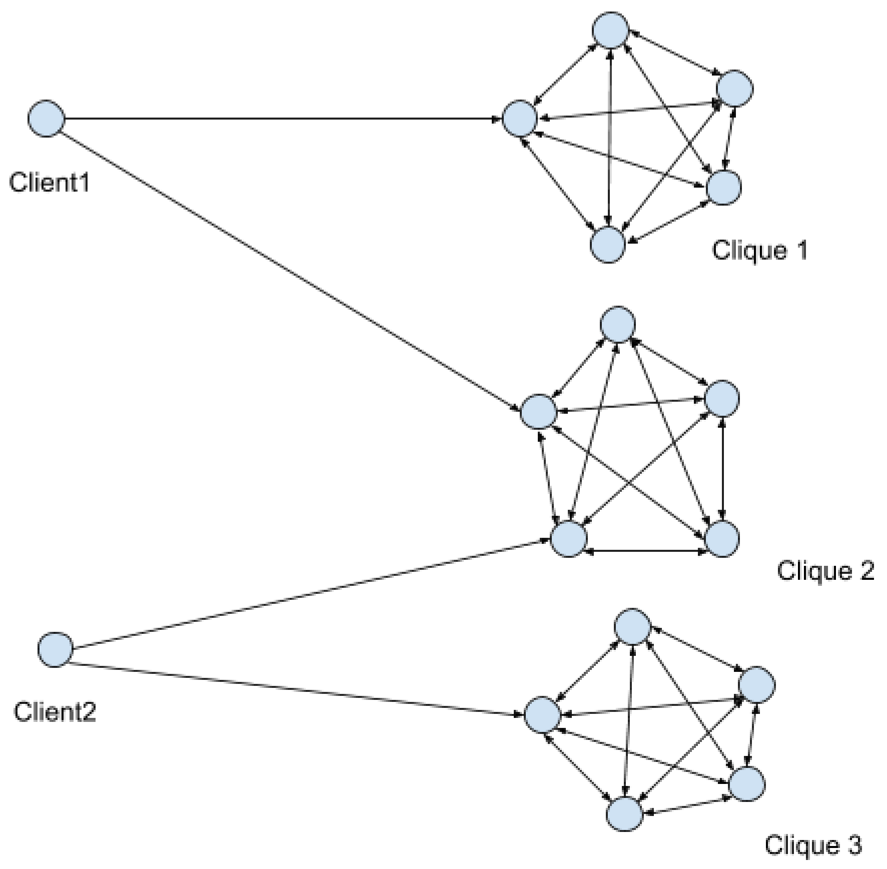


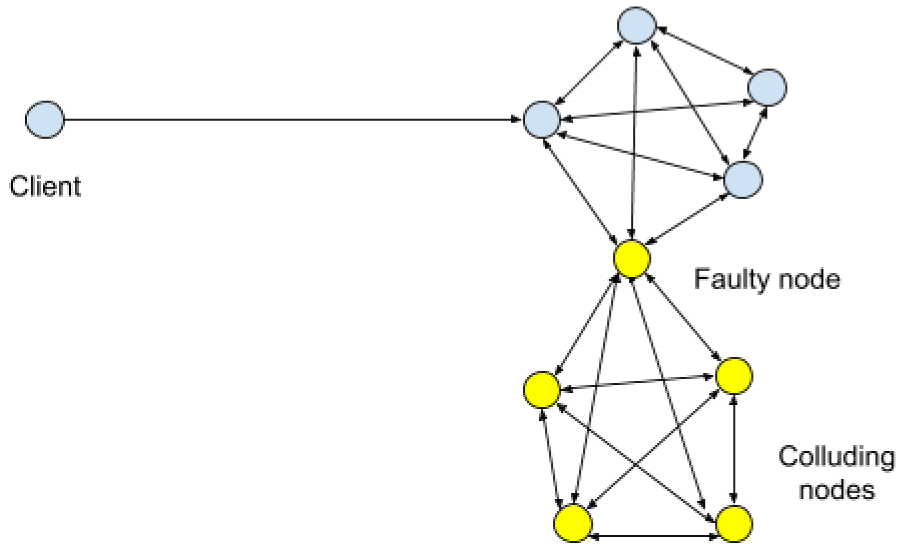
With the above algorithm, client1 has clique 1 and 2, and client 2 has clique 2 and 3.

Note that the graph is not representing network topology. Only assumption is that each node can be reached with the URL. In other words, failure nodes will not block any connections once the trust graph is established as servers do not talk each other.

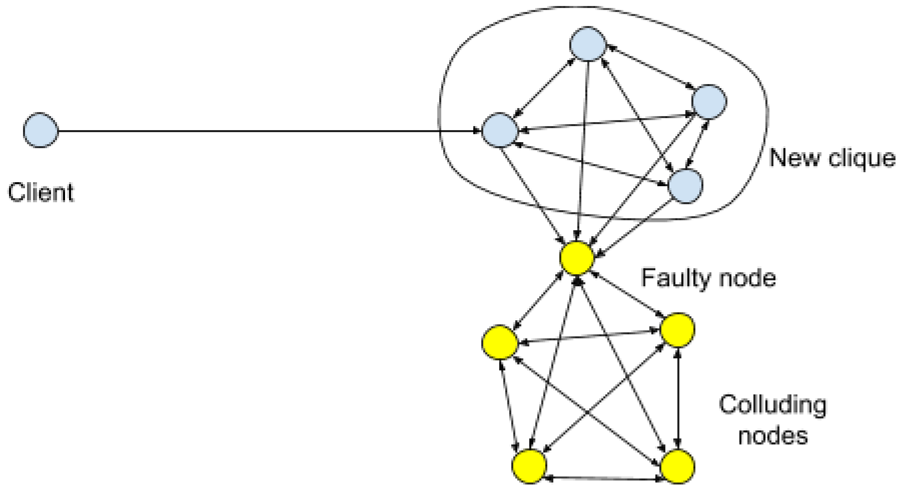
Any node can join the network without authentication, but it cannot join any existing clique unless it gets signed by all members of the clique. Put it in another way, unauthorized nodes can be members of the kv quorum, but they cannot join the authority quorum.

Sybil attack

As above, anyone can make up as many nodes as they want and have them join the network but those nodes cannot outnumber of authorities unless some amount of existing nodes in the cliques are compromised. Also we show the quorum system is immune to the sybil attack even in that case. Faulty nodes may try to outnumber the non-faulty nodes by making cliques:



But with the algorithm (g) any node cannot be a member of more than one clique, therefore the compromise node cannot extend the clique with faulty nodes. If it wants to make a faulty clique, the faulty node has no choice but severing links to all members itself, which results in kicking itself out of the clique.



Our quorum system requires that all quorum cliques need to agree on <k,v> to accept the value. Even if the client has a faulty clique it will not be deceived but it is possible to sabotage normal operations. We take on the safe side. The client can choose which cliques are trustworthy and exclude other cliques from the behavior of each clique. See below for revocation.

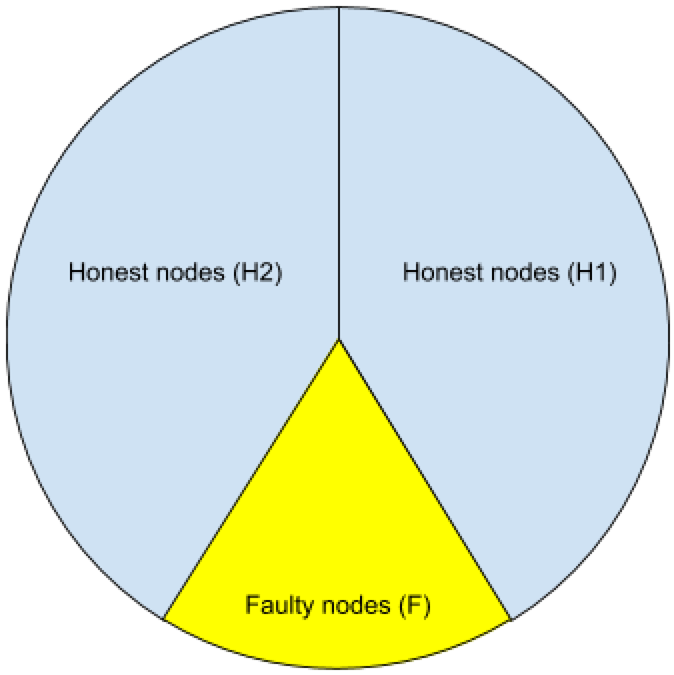
Revocation

Revocation is the only way to keep the system sound in the long run. Even if the quorum system excludes uncertified keys by majority vote, excluding compromised nodes will increase the fault tolerance rate drastically.

Each node severs the trust link independently without consulting others. It is detected in both "read" and "write" protocols when a node signs both $< x, t, v >$ and $< x, t, v' >$ where $v \neq v'$. Also servers revoke clients when it detects a client signing different values with the same timestamp as well. Once a node is revoked, the node will be excluded from the graph and there is no way to restore it. See the security analysis for the detection rate.

Security Analysis

We look into attacks against the fundamental property: $READ(Q_1, x) = READ(Q_2, x)$ for $\forall Q_1, Q_2 \in QS$, which is known as equivocation attack.
The best that attackers can do is divide a clique into two sets and ask each set to sign $< x, t, v >$ and $< x, t, v' >$ separately. Then do the "write" protocol for the target nodes with collected signature sets S and S'. Honest servers will refuse the request because it does not satisfy the basic b-masking quorum condition: $|S| \geq b + 1$. But with b colluding nodes, the attack will succeed.



The attacker sends echo requests to $\{H_1 \cup F\}$ and $\{H_2 \cup F\}$ separately:

$c \rightarrow H_1 + F$: "echo" $< x, t, v >$

$c \rightarrow H_2 + F$: "echo" $< x, t, v' >$

The maximum number of signatures dishonest clients can get is $b + (n - b)/2$. Therefore, to overcome the equivocation attack we need $n - b > b + (n - b)/2 \Rightarrow n > 3b$.

Accepting signed data on write

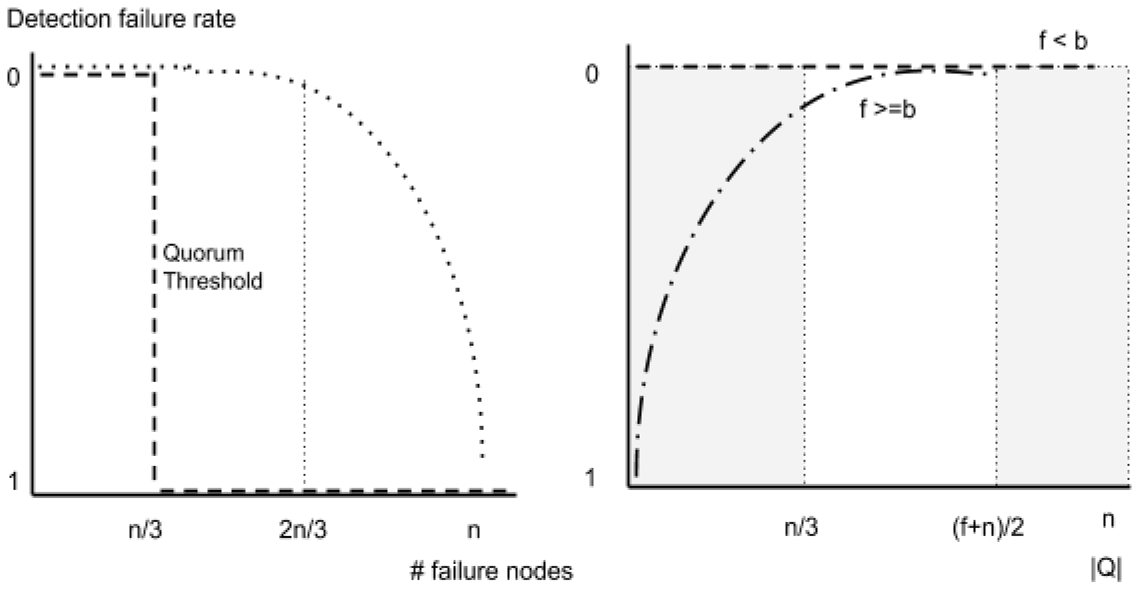
Each node that has received the write request verifies S with cliques that cover itself. If S includes enough signatures signed by the members of the cliques, the node will accept the message: $ACCEPT(<x, t, v, sig, S>) = \forall QC_i \in g(self),\ |S' \cap QC_i| \geq b_i + 1$ where $S' = \{s \in S \mid Verify(s, <x, t, v, sig>) = true\}$.
[Note: nodes in a KV quorum but not in an Authority quorum, i.e., $Q \in QS_B \setminus QS_A$, can make small cliques that have the size of less than 4. Those nodes will not be involved in signing therefore they are excluded from the above cliques.]
Equivocation check has to be done on write if a value for $<x, t>$ is already stored in the node. If the new request has the same variable (x) and timestamp (t), the node will not only reject the message but revoke all signers including the issuer who have signed on both $<x, t, v>$ and $<x, t, v'>$. It is unlikely to be able to detect malicious action here when malicious clients issue the write request -- they should carefully choose the sets of servers that will not intersect each other. However, the write request can be issued on the read request as writeback, and in this case it is possible that a set of nodes receives a write request $<x, t, v', sig', S'>$ which conflict with $<x, t, v, sig, S>$ stored in the storage. See below for the detection rate.

Detecting equivocation on read

The system is intact as long as each clique keeps more than $2b + 1$ non-faulty nodes. Dishonest clients + colluding servers cannot do either 1) getting in the way for honest clients to read values, 2) deceiving honest clients with equivocation. When the number of faulty nodes exceeds the threshold, it is possible that honest clients no longer can collect enough number of valid responses.
From the threshold to n $(= |U|)$ all servers including non-faulty servers will accept forged values, however, it is still possible to detect malicious actions on read by choosing a quorum randomly. The failure probability:

$$Fp = Pr[Q \cap H_1 \neq 0 \wedge Q \cap H_2 \neq 0] = 1 - Pr[Q \subseteq F \cup H_i] = 1 - ((n + f)/2n)^{|Q|}$$

when $f > b$ and $|Q| < (f + n)/2$ where f is the number of faulty nodes,
assuming the size of $H_i,\ i = \{1, 2\}$ are the same.



In the case of $f < b$ the detection rate is always 100% because it is guaranteed that clients can always find a valid value and anything other than that is the result of malicious actions. When the number of faulty nodes exceeds the threshold, i.e., $f \geq b$, it will be possible that the client cannot detect the malicious action. Since the minimum quorum size is $(n-1)/3$ it does not need to consider the case where $|Q| < n/3$. Also, if the size exceeds $(f+n)/2$ any quorum always includes at least one node from each H_i which makes the detection rate 100%. For example, assume we choose a quorum $|Q| = 3b+1$ out of $n = 4b+1$, which is the default setup of the kv quorum system, the detection rate is 100% up to $f = 2b$ failure nodes.

After discarding those f nodes, if there are still more than $b+1$ valid $< x, t, v, sig, S >$, the read operation will succeed and return the value. Nodes that are involved in the malicious action will be revoked immediately, which will change the quorum system and thresholds.

Roaming Service

BFTKV provides strong data integrity on values stored in the BFTKV storage. It is assured that the data retrieved from a quorum has not been tampered and it is also fresh. On the other hand, data privacy (or data secrecy) is user's responsibility. If user does not want to propagate data to a quorum as-is, they have some options such as using a hash over the data and writing it to BFTKV with the key. The actual data can be stored in a private repository. When the data is retrieved its hash value will be compared with the value on BFTKV.
Another possibility is encrypting data before writing to BFTKV. But, what if the user wants to retrieve the data on another device? The decryption key needs to be taken to the device securely, which is not straightforward whether it is a symmetric or asymmetric key. BFTKV provides a password based roaming service for that purpose. Users do not need to carry around

the key. Only password is necessary to encrypt and decrypt data anywhere. Password encryption schemes tend to be weak because users tend to use weak passwords. The BFTKV password roaming scheme mitigates the weakness utilizing the quorum system. Members of a quorum collaboratively verify the password using Shamir's secret sharing scheme. Like the quorum system, it needs $2f+1$ non-faulty nodes to authenticate the password and the system is immune to offline dictionary attacks unless f nodes are compromised. BFTKV uses SRP for authentication and key exchange, which resists dictionary attacks in between server and client. Combining those two schemes, it is difficult for attackers to guess even weak passwords.

Setup & Encryption

In the (k,n) threshold scheme, client constructs a $k-1$ degree polynomial $f(x) = a_0 + a_1x + a_2x^2 + ... + a_{k-1}x^{k-1}\ mod\ q$ with random coefficients and the secret $a_0 = S \in Z_q$.
Calculate $n = |Q|$ pairs $(i, f(i))$ and sends $< y_i, v, salt >$ to each quorum member, where

$y_i = f(i) + g^{\pi'}\ mod\ q$
$v = g^x\ mod\ p$
$x = \pi S\ \ mod\ q$
$\pi = Int(h(salt,\ passwd))\ mod\ p$
$\pi' = Int(h(passwd))\ mod\ q$
p and q are both prime numbers such that $p = 2q+1$ (i.e., p is a safe prime), g is a generator on Z_q .

$< i,\ y_i, v, salt >$ is stored at each server associated with the variable. The coefficients, shared secret and salt must be randomly generated for each variable.
To encrypt user data, use a symmetric algorithm with a key $H(x)$. The encryption algorithm, key length and mode are users' choice. To update the encrypted data, users can reuse the same encryption key, password and shared secret for the same variable.

Authentication & Decryption

C : generate a random number $a,\ 1 < a < q$
$C \rightarrow q_i$: $X = g^{a'}\ mod\ p$ with the variable var, where $a' = a - g^{\pi'}\ mod\ q$
q_i : generate a random number b_i
$KS_i = (Xv^{u})^{b_i} = (g^{b_i})^{(a'+ux)}\ mod\ p$
$C \leftarrow q_i$: $Y_i = X g^{y_i}\ mod\ p,\ B_i = kv + g^{b_i}\ mod\ p,\ salt,\ E_{KS_i}(Sign_i(var), X \| B_i)$
< collect $f+1$ responses from the quorum >
C : calculate $g^{f(i)} = Y_i / g^a = g^{a-g^{\pi'}} g^{f(i)+g^{\pi'}} g^{-a}\ mod\ p$
C : calculate the lagrange basis polynomial from $l_j = \Pi_{1 \le m \le f} i_m/(i_m - i_j)\ mod\ q$ and $g^{f(i)}$, then get $g^S = \Pi_j\ (g^{f(j)})^{l_j} = g^{\Sigma f(j) l_j}$
< calculate the shared key between C and q_i >
C : $KS_i = (B_i - k(g^S)^{\pi})^{(a'+ux)} = (kv + g^{b_i} - kg^{\pi S})^{(a'+ux)} = (g^{b_i})^{(a'+ux)}\ mod\ p$
$Sig_i = D_{KS_i}(E(\bullet), X \| B_i)$

< collect $2f + 1$ decrypted signatures >
C : $SS = \{Sig_1,\ Sig_2,\ ...,\ Sig_{2f+1}\}$
< get the encrypted data from another quorum >
$C \rightarrow Q'$: $< var, SS >$
$q'_i \in Q'$: verify SS the same way as the write protocol
$C \leftarrow Q'$: $< var, E(value), t, sig, SS' >$
< do the same as the read process and get the final $E(v)$ >
C : decrypt $E(value)$ with $H(\pi g^S)$

$k = H(p, g),\ u = H(X, B_i)$. $E_k(P,\ A)$ is an AEAD mode with the associated data A and the plain text P.

- The above protocol is done by a client and servers without requiring an intermediate server that tends to act as a proxy server to perform reconstructing the shared secret
- Even if each server is compromised it is infeasible to reverse πg^S as unlike the password the value is nearly random and the size is quite big (The protocol can be seen as a scheme to convert a password to a large random value)
- Even if f servers are compromised still the attacker needs to do a dictionary attack against π to get the password
- Compromised servers cannot pretend as a client in the SRP authentication unless they have the password π
- $E_{KS_i}(Sig_i(var), X\|B_i)$ is sent before the server confirms the evidence. This allows attackers to guess the password by issuing the protocol again and again without getting attention very much because the server cannot distinguish a legitimate protocol from brute force. It is possible to confirm the evidence before revealing any information to clients just like the original SRP does but even if we do so just one compromised server will make it possible to verify the result offline. Therefore, the server should keep the track of authentication process and if the client doesn't send out legitimate signatures with many trials the server will prevent the request from the client for some period or if we are more strict the server can revoke it. This way even if some of servers are compromised the rest of them will stop the attack.

Update

Client and a quorum do the authentication and key exchange just the same as the read process above. Use the same encryption key $K = H(x)$ to encrypt the new value. Then,

< collect signatures SS using the same AKE >
C: $EM = E_K(v)$
$C \rightarrow Q$: $write(Q,\ EM\ )$ with SS

Client verifies the hash value to finish the update.

Threshold Signatures

The quorum system of BFTKV supports multiple signatures over arbitrary data as follows: Client signs data with its own BFTKV key just the same as the case of “write”: $sig = Sign(tbs)$. Remember, the BFTKV signature scheme tags the certificate with the signature value in sig. The signature is opaque from outside of BFTKV. The user just keeps sig along with the original data. To verify the data, sig is verified with the signer’s certificate first, then the certificate is verified with the quorum certificate.

Besides the quorum signature illustrated above, BFTKV provides another signature scheme based on threshold signatures. Threshold signatures are useful when the verifier is not a BFTKV node, i.e., when existing systems use ordinary signature schemes, such as X.509 or Bitcoin Tx. BFTKV supports three threshold signature algorithms: RSA (PKCS1.5), DSA and ECDSA.

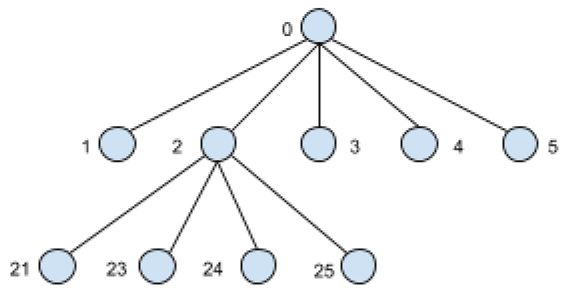
RSA

Since $\varphi(n)$ in RSA must be kept as secret as d Shamir’s shared secret cannot be applied straightforwardly; to calculate the lagrange interpolate $l_j = \Pi_{1 \le m \le f} i_m / (i_m - i_j) \ mod \ \varphi(n)$ we need a multiplicative inverse of $i_m - i_j$ on $\varphi(n)$. Shoup [] resolves this problem by getting rid of multiplicative inverse on a cyclic group all together but it requires a different construction of the RSA parameters than the standard way. Therefore his method cannot be applied to existing RSA keys. (If we can generate RSA keys ourselves the method will be adequate.)

The method used for BFTKV is an extension of the simple (n, n) threshold scheme, i.e., the private key is divided into n sub keys such as $d = \sum_{i=1}^{n} d_i \ mod \ \varphi(N)$ and the partial signatures $s_i = m^{d_i} \ mod \ N$ are combined into the signature as:

$$s = \Pi_{i=1..n} s_i \ mod \ N = M^{\sum_{i=1}^{n} d_i \ mod \ \varphi(N)} \ mod \ N = M^d \ mod \ N \ .$$

To make the (n, n) threshold scheme a somewhat (k, n) threshold scheme, we construct the partial keys recursively. In the following tree, if a node (2) is a faulty it will be compensated by other nodes (1, 3, 4, 5) for the keys (21, 23, 24, 25) respectively, i.e., $s = \Pi_{i \in \{1,2,3,4,5\}} s_i \ mod \ N$ where $s_2 = \Pi_{i \in \{21,23,24,25\}} s_i \ mod \ N$.



DSA, ECDSA

BFTKV implements a DSS threshold scheme introduced by Gennaro et al. [6] Since the scheme has a restriction such that $n \geq 2k$ in the (k, n)-threshold scheme, we no longer be able to use the quorum threshold for (k, n). But, we follow the protocols between the client and a quorum, i.e., the client sends a signing request to a quorum (multicast the message to all quorum members), then collect the responses. Our signing protocol consists of three phases:

1) Collect joint shared secrets generated by each quorum member
2) Distribute the secrets to the quorum and calculate $r = g^{k^{-1}} \, mod \, p \, mod \, q$ where k is the joint Shamir's shared secret (i.e., $k = \sum k_i$)
3) Distribute r to the quorum and calculate $s = k(m + xr) \, mod \, q$ from each $s_i = k_i(m + x_i r) \, mod \, q$ returned from each quorum member

Applications

Decentralized PKI using a collective consensus protocol

User authentication is a long-standing problem for end-to-end systems. Even if we have semantically secure cryptographic protocols to exchange data between users, if it was with a wrong one, the whole security system would not make sense. On the other hand, once we have a robust user authentication scheme, we can build up many kinds of security systems on top of that, such as PGP and Signal[7]. Our goal is to construct an infrastructure to exchange public keys that represent users' identities. Exchanging public keys can be done in person, using a QR code, confirming the fingerprint of public keys, etc. Those methods seem to be relevant for some situations, such as sending money. Also, public key infrastructures using central authorities, such as X.509 which is based on chain of trust, are widely used. A PKI like X.509, however, still have a problem when issuing a certificate to each end user. CAs issue certificates to corporates, organizations, and individuals based on trustworthiness of requesters but for end

[6] "Robust Threshold DSS Signatures", R., Gennaro, et al.
[7] https://whispersystems.org/docs/specifications/x3dh/

users whose authenticity is not easy to be proven, we have the same basic issues. From end users' point of view, blindly relying on a central authority based on its authenticity is no longer secure and contradict the end-to-end philosophy.
Our proposed PKI does not "strongly" rely on central authorities, yet it does not require to exchange public keys in person. Here are the high level system requirements:

- Scalability -- the system can grow without affecting the current running services
- Transparency -- anyone can monitor every system activity
- Quantifiability -- security and efficiency can be formally analyzed
- Robustness -- the system has to recover from erroneous situations by itself
- Privacy -- the system should not reveal unnecessary information about users
- Non-interactivity -- a client may not be able to interact peers before sending a message. This particular requirement makes it difficult to design a system that guarantees the "what I saw is what you see" concept. SMTP, for example, is not a mutual explicit authentication protocol. When an email is encrypted then sent out, if it is encrypted with a wrong key, it will be too late -- someone in the middle could read the email when the recipient receives the email and notice that the encrypted email is not actually for her.

Key lookup service

The system can be used to enhance security of the HKP[8] service. HKP is a simple dictionary server; a user looks up PGP keys of recipients with email address, user ID or key ID. The sender decides if she trusts the PGP key by who signed the key. If there is no signer the sender trusts, it is up to her if she goes ahead. The system helps her decision.
A typical scenario: Service provider (SP) calculates a VRF index[9] from the user ID to keep their privacy and publish the VRF public key to everyone. SP registers their PGP keys on behalf of users to the system: $WRITE(Q, vrf, H(PGP))$. When a sender looks up the key, SP will return the VRF index along with PGP. Users can verify the PGP by $READ(Q, vrf) = H(PGP)$. The sender also can double-check the log and signers if she wants to.
Email (or client apps) clients, on behalf of users, can check periodically that the value is not altered by someone else. Even if the <k, v> slot is protected by the quorum certificate, it will be a good practice for users to check it from time to time. She will know who did the unauthorized mutation from the signers of the key. Malicious actions retains in the log forever in all quorums.

Transparency Framework

The system is also useful for a transparency framework such as CONIKS[10]. CONIKS uses Merkle tree to check if the sender and receiver see the same key set. Since the system guarantees $READ(Q_1, x) = READ(Q_2, x), \ \forall Q_1, Q_2 \in QS$ all trees constructed from the

[8] https://tools.ietf.org/html/draft-shaw-openpgp-hkp-00
[9] S. Goldberg, et. al., "Verifiable Random Functions (VRFs)" [https://tools.ietf.org/html/draft-goldbe-vrf-00#ref-SECG1]
[10] https://coniks.cs.princeton.edu/about.html

quorum system must be the same, i.e., any non-malicious CONIKS node will maintain the same tree which will serve well to keep its failure probability as low as expected.

Tree Head Store

Another example of a use of the system is to store the Merkle tree head in a specific slot so everyone can see the same value and log. This example can be more private than above. Only service provider maintains the user's ID and key, and construct Merkle tree. Only the tree head is published publicly. On the other hand, security relies on the entity that maintains user data.

Appendix

A. Client Key Generation

To be a BFTKV client, a PGP key pair (see Implementation Note below) needs to be generated and signed by a subset of quorum members. The BFTKV ID must have the following form: "real name <UID>". UID is used to restrict access with the TOFU policy. Users can make multiple PGP key pairs with the same UID.
A generated PGP key (the public part only) needs to get signed by quorum members the client trust. How to prove users' credential depends on applications. If the client application is associated with an email system, for example, email service providers may provide a method to prove that the user ID (i.e., email address) actually belongs to the user.

Here, as the default method that does not depend on applications, we show a password based registration method utilizing the BFTKV password roaming service.

Setup (Enrollment)

User generates his PGP key on his own. When the user gets the PGP key signed he provides a password along with the PGP key. With the roaming scheme, each server remember $\{y_i, g^x\}$ associated with UID.

Key recovery (secondary key generation)

When the user wants to generate another key which has the same UID for another device, or if the user has lost the key for the device, the user generates a new key on his own and gets it signed with the password he used at the time of enrollment. Each server verifies the password following the BFTKV roaming scheme and share a session key SK with the (new) client. Then, the client sends the new PGP key with the collective signatures, and gets back a signed PGP key:

< do the password roaming AKE and collect SS >
$C \rightarrow q_i$: $PGPkey,\ SS$

```
$C \leftarrow q_i$:        $\{PGPkey\}_{q_i}$    // signed PGP key
< collect enough number of signed keys >
$C$:                       merge the all signatures into the PGP key
```

B. Implementation Notes

We define (go) interface for:

- Quorum system
- Transport layer (including transport security)
- Node (certificate)
- Crypto package
    - signature scheme
    - message encryption / signature
    - collective signature
    - Keyring
    - RNG
- Storage

We implement (as of now):

- Quorum system with WoT
- Transport with HTTP
    - Transport security with PGP message encryption / signature
- Certificate with PGP key
    - Trust graph to manage nodes
- All crypto functions with PGP
    - PGP keyring to store certs, private key and revocation list
    - PGP key for certificate
    - PGP signatures in PGP key to construct the graph
    - PGP encryption / signature for transport security
    - PGP signature to sign $< x, t, v >$
    - PGP signature for collective signature
    - PGP User ID for the URL
- Storage with (plain) Unix file to store the value with the filename: “variable (hex string).timestamp”, or with leveldb.

In golang, we use “golang.org/x/crypto/openpgp” for the PGP operations. Except PGP, we use the standard library only.

All messages are encrypted with the PGP key of recipients. With the PGP encryption scheme, a message is encrypted only once with all recipient’s keys, then signed by the self key. The same PGP packet is sent out to each recipient.

The collective signature is just a series of the PGP signature packet in the current implementation. The reason why the interface defines the collective signature separated from the signature scheme is because of a possibility of replacing it with a threshold signature scheme in the future.

PGP Key

The following PGP packets are used in the system.

Public-Key Packet

Must include the primary public key. The key is used to verify the signature to make the trust graph within the quorum system.

Signature Packet

Represents trust incoming edges from signers. Must include the self-signed signature as specified in OpenPGP [ref].

Sub key packets

Inside the signature packet, at least one encryption key has to be included. The system uses the key for transport-security as well as encrypting messages.

User ID Packet

Must have the format “Real name (URL)” or “Real name <email address>”. Each server must have the former format and end user clients must have the latter one. The “email address” part will be used as a unique ID to check TOFU. Note that the unique ID can be same among keys which have different key ID (the hash value of the primary key).

User Attribute Packet

With subtype = 101,
Can include any data necessary for “email address proof”, e.g., DKIM, SAML, OpenID.

Revocation List Packet

A list of PIDs the node no longer trusts while it trusted before (therefore it signed the PGP certs).