NTP Security Algorithms

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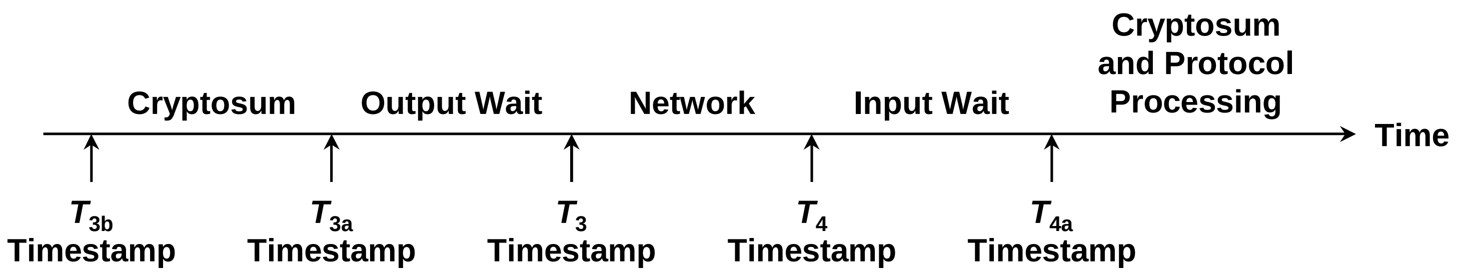
Sir John Tenniel; *Alice's Adventures in Wonderland,*Lewis Carroll

Symmetric key and public key cryptography

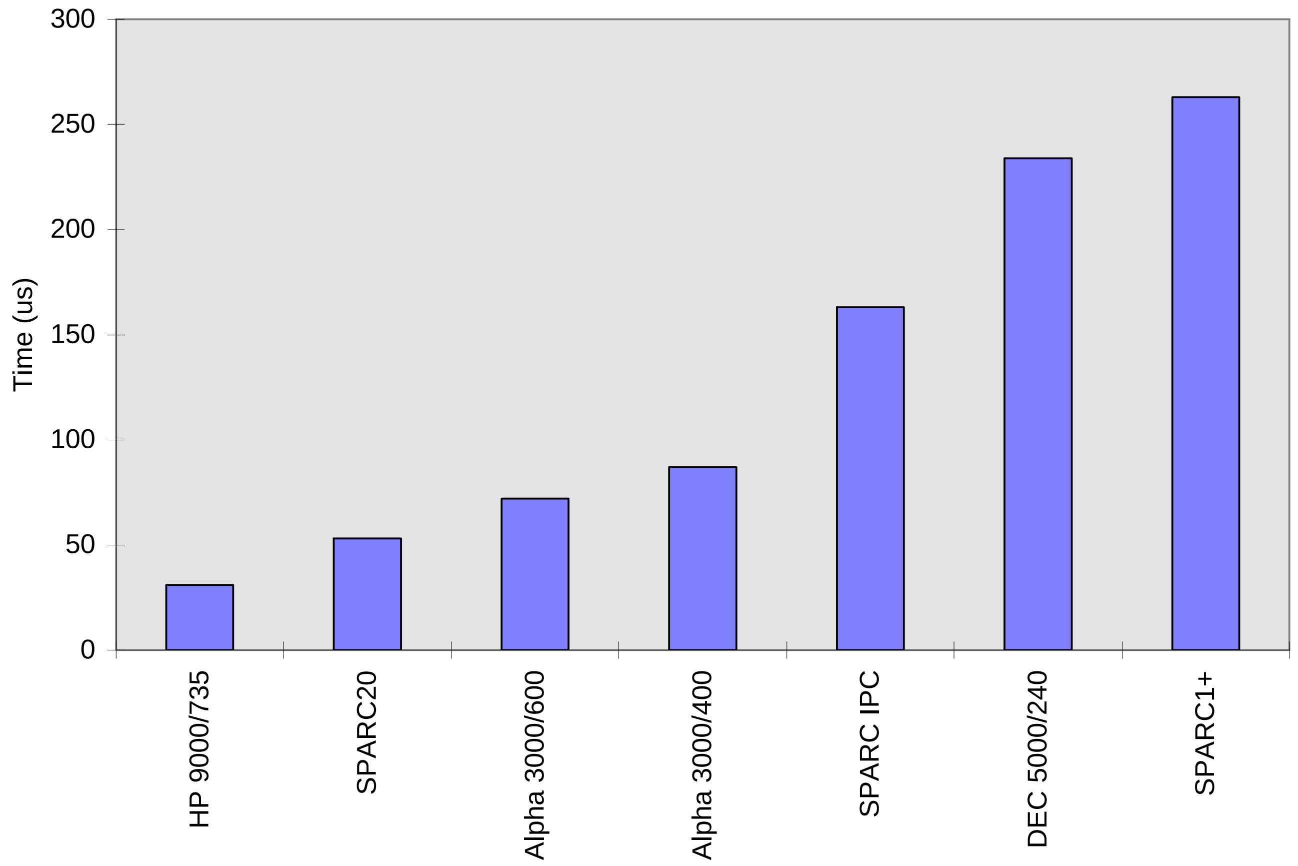
- Public key cryptography
  - Encryption/decryption algorithms are relatively slow with highly variable running times depending on key and data
  - All keys are random; private keys are never divulged
  - Certificates reliably bind server identification and public key
  - Server identification established by challenge/response protocol
  - Well suited to multicast paradigm
- Symmetric key cryptography
  - Encryption/decryption algorithms are relatively fast with constant running times independent of key and data
  - Fixed private keys must be distributed in advance
  - Key agreement (Diffie-Hellman) is required for private random keys
  - Per-association state must be maintained for all clients
  - Not well suited to multicast paradigm

Message propagation time budget



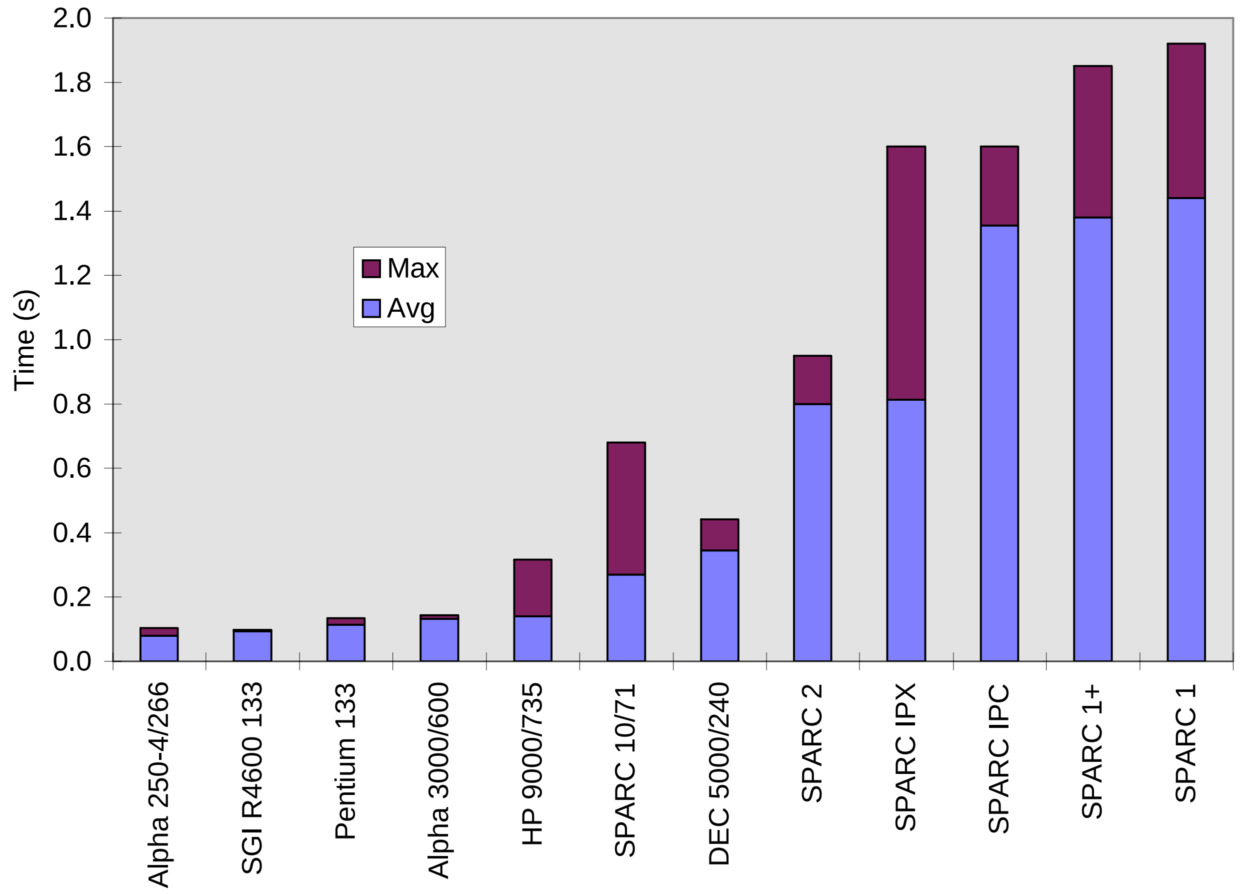
- We want T_3 and T_4 timestamps for accurate network calibration
  - If output wait is small, T_{3a} is good approximation to T_3
  - T_{3a} can't be included in message after cryptosum is calculated, but can be sent in next message; use T_{3b} as best approximation to T_3
  - T_4 captured by most network drivers at interrupt time; if not, use T_{4a} as best approximation to T_4
- Largest error is usually output cryptosum
  - Private-key algorithms (MD5, DES-CBC) running times range from 10 µs to 1 ms, depending on architecture, but can be predicted fairly well
  - Public-key algorithms (RSA) running times range up to 100 ms, depending on architecture, but are highly variable and depend on message content

MD5 message digest computations



- Measured times to construct 128-bit hash of 48-octet NTP header using MD5 algorithm in RSAREF

MD5/RSA digital signature computations



- Measured times (s) to construct digital signature using RSAREF
- Message authentication code constructed from 48-octet NTP header hashed with MD5, then encrypted with RSA 512-bit private key

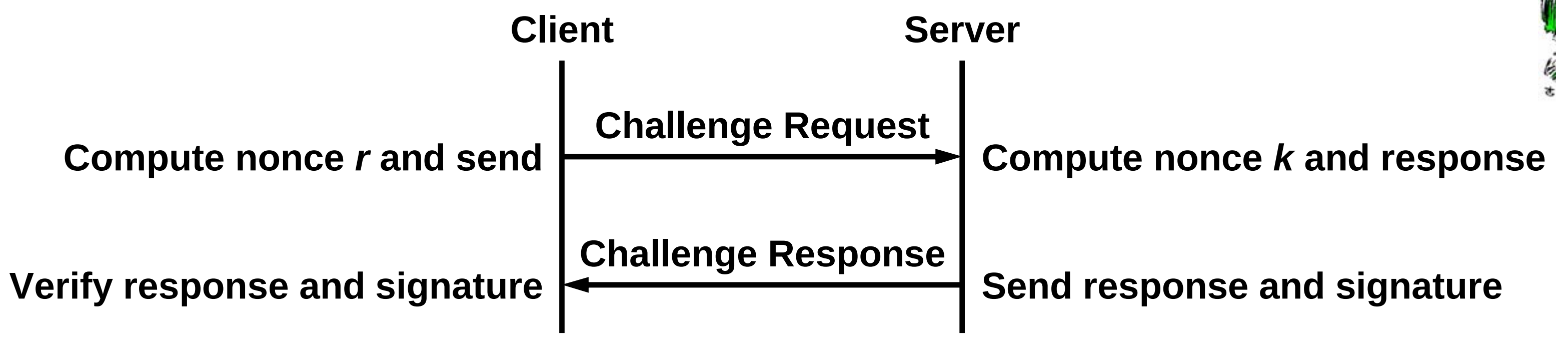
Certificates

- A private/public key pair and self signed host certificate are required for each host.
  - Certificates are in X509 version 3 format valid for one year.
  - The serial number is the NTP seconds of generation to insure uniqueness.
- Extension fields are used to convey identity parameters and whether the certificate is private or trusted.
  - The required Basic Constraints field contains the string “critical,CA:TRUE”, indicating the host can act as a certificate authority.
  - The required Key Usage field contains the string “digitalSignature,keyCertSign”, indicating the certificate is valid for digital signatures and to sign other certificates.
  - The optional Extended Key Usage field contains the string “private” indicating a private certificate (PC identity scheme) or the string “trustRoot” indicating a trusted certificate. By definition, private certificates are trusted.
  - The optional Subject Key Identifier field contains the public key for the GQ identity scheme.

Signature operations

- Public keys, certificates and leapseconds files can be read from local files or sent over the net using the Autokey protocol.
- Cryptographic values are signed only when the host is synchronized.
  - Filestamps record the NTP seconds when the file was created. These are proventic data and provide a reliable total ordering of creation epoches.
  - Timestamps record the NTP seconds when the data were last signed. These are proventic data only when the sender is synchronized and provide only a partial ordering of signing epoches.
- Cryptographic values derived from files and received over the net are signed only when they are created or changed and in addition at refresh intervals of about one day.
- Autokey values are signed when the key list is regenerated, about once per hour.
- Cookie values are signed when sent.
- Identity values are signed when sent.

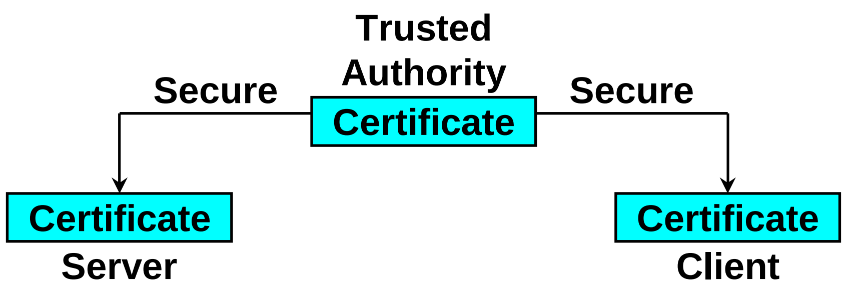
Identification exchange



Client
Server
Compute nonce *r* and send
Challenge Request
Compute nonce *k* and response
Verify response and signature
Challenge Response
Send response and signature

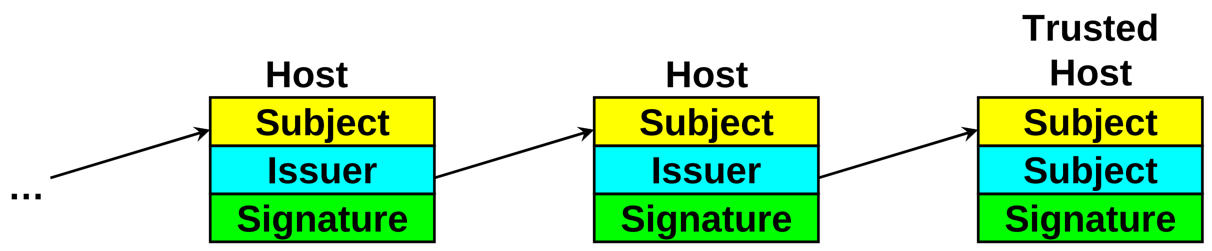
- This is a challenge-response scheme
  - Client Alice and server Bob share a common set of public parameters and a private group key *b*.
  - Alice rolls random nonce *r* and sends to Bob.
  - Bob rolls random nonce *k*, computes a one-way function *f*(*r*, *k*, *b*) and sends to Alice.
  - Alice computes some function *g*(*f*, *b*) to verify that Bob knows *b*.
- The signature prevents message modification and binds the response to Bob's private key.
- An interceptor can see the challenge and response, but cannot determine *k* or *b* or how to construct a response acceptable to Alice.

Private certificate (PC) identity scheme



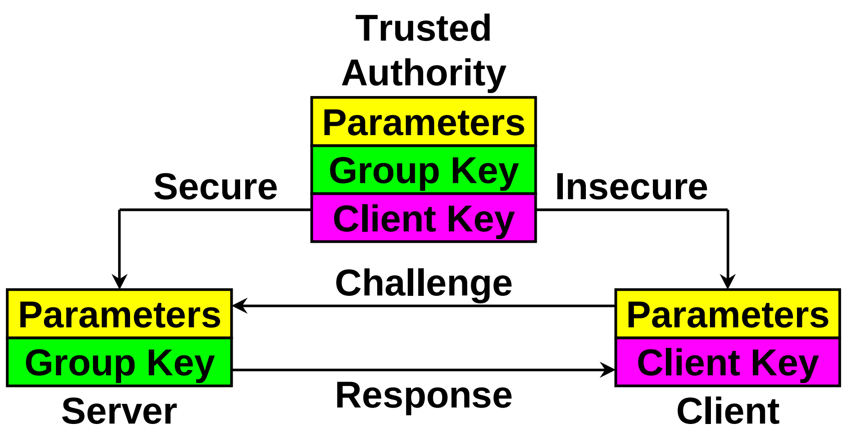
- TA generates a certificate marked private and transmits it by secure means to all servers and clients.
- The certificate is never divulged outside the group and never presented for signature.
- An identity exchange is not necessary.
- Refreshing certificates is a major problem

Trusted certificate (TC) identity scheme



- Each certificate is signed by the issuer, which is one step closer on the trail to the trusted host (TH).
- The trusted host certificate is self-signed and self-validated.
- This scheme is vulnerable to a middleman masquerade, unless an identity scheme is used.
- A trusted authority (TA) generates the group key (if used) which has the same name as the TH subject name.

Schnorr (IFF) identity scheme

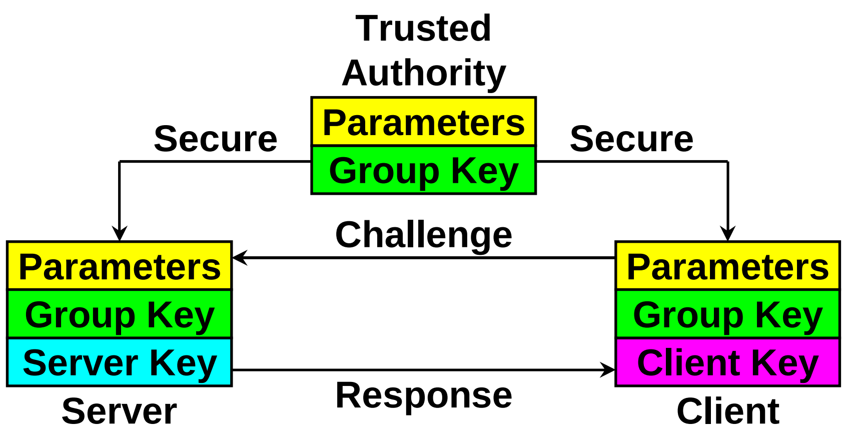


- TA generates the IFF parameters and keys and transmits them by secure means to all servers and clients.
- Only the server needs the group key; the client key derived from it is public.
- IFF identity exchange is used to verify group membership.

Schnorr (IFF) identification scheme operations

- Schnorr (IFF) scheme is based on DSA principles.
  - Public parameters include 512-bit prime p, 160-bit prime q that divides $p - 1$ and generator g of p such that $g^q = 1 \bmod p$.
  - TA rolls private random group key b and distributes to all servers in the group using secure means.
  - TA computes public $v = g^{q-b} \bmod p$ and distributes to all clients in the group using insecure means.
  - Client Alice rolls random nonce r ($0 < r < q$) and sends to server Bob.
  - Bob rolls random nonce k ($0 < k < q$), computes $y = k + br \bmod q$ and $x = g^k \bmod p$, then sends (y, hash(x)) to Alice.
  - Alice computes $g^y v^r \bmod p$ (which is $g^k \bmod p$ without revealing k), then verifies hash(g^k) matches hash(x).
- If the parameters or group key are changed, all group members must be updated.

Guillou-Quisquater (GQ) scheme



- TA generates the GQ parameters and keys and transmits them by secure means to servers and clients.
- Server generates a GQ private/public key pair and certificate with the public key in an extension field.
- Client uses the public key in the certificate as the client key.
- GQ identity exchange is used to verify group membership.

Guillou-Quisquater (GQ) identity scheme operations

- Guillou-Quisquater (GQ) scheme is based on RSA principles.
  - Public parameters include 512-bit modulus *n* a product of two large primes *p* and *q.*
  - TA rolls private random group key *b* and distributes to all group members using secure means.
  - Each group member rolls random private nonce *u* $(0 < u < n)$ and computes public $v = (u^{-1})^b \bmod n$, then saves both for future reference. The *v* is conveyed in an extension field of the member's public certificate.
  - Alice rolls random nonce *r* $(0 < r < q)$ and sends to Bob.
  - Bob rolls random nonce *k* and computes $y = ku^r \bmod n$ and $x = k^b \bmod n$, then sends (*y*, hash(*x*)) to Alice.
  - Alice computes $y^b v^r \bmod n$, which simplifies to $k^b \bmod n$, then verifies hash(k^b) matches hash(*x*).
- If the parameters or group key are changed, all group members must be updated; however, a member can refresh *u*, *v* and certificates at any time.

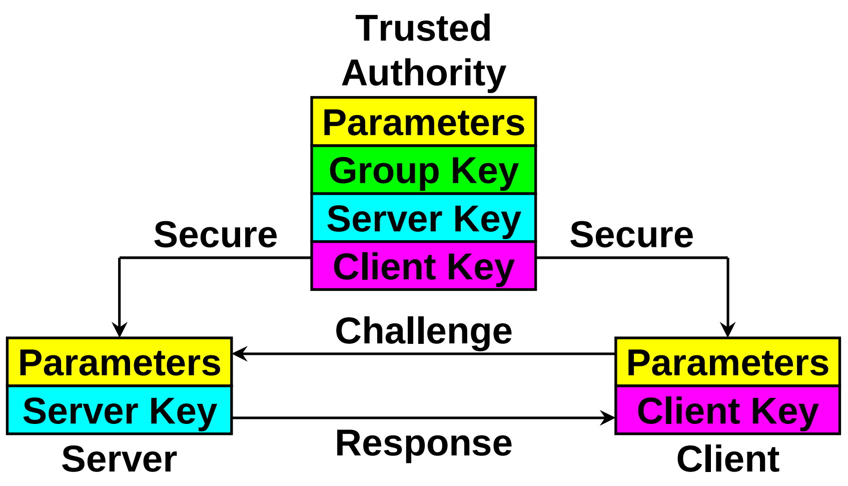
Mu-Varadharajan (MV) identity scheme – setup I

- Mu-Varadharajan (MV) identity scheme is based on DSA principles.
- TA generates private parameters and server coefficient *A*.
  - TA generates *n* distinct primes $s_1, \ldots, s_n$, their product *q*, prime $p = 2q + 1$ and generator *g* of *p* such that $g^q = 1 \bmod p$. These parameters are generated by a probabilistic algorithm such that *p* has approximately 500 significant bits. Note that the multiplicative group Z_q^* includes only those elements *x* where gcd(*x*, *q*) = 1.
  - TA generates *n* roots $x_1, \ldots, x_n$ of the polynomial $p(x) = a_0 + a_1x + a_2x^2 + \ldots + a_nx^n \bmod q$, then solves for $a_0, \ldots, a_n$ using a fast recursive algorithm.
  - TA computes functions $g_{ij}(a_i, x_j)$ ($i = 0, \ldots, n$; $j = 1, \ldots, n$) mod *p* as the matrix *G* with *i* rows corresponding to coefficients a_i and *j* columns corresponding to roots x_j. By construction, the product of all elements of *G* is unity. The functions g_{ij} are described elsewhere.
  - Let *S* be the submatrix g_{ij} (i = 0, …, $n - 1$; $j = 1, \ldots, n$); i. e., all but the last row, and *C* the vector g_{nj} ($j = 1, \ldots, n$); i.e., only the last row. The server coefficient is *A* computed as the product of all elements of *S* mod *p*; this need be computed only once; *S* will not be used again.

Mu-Varadharajan (MV) identity scheme – setup II

- TA generates private server encryption and client decryption keys.
  - TA rolls private random group key b ($0 < b < q$) and computes its inverse b^{-1} mod q.
  - For each s_i, TA computes s_i' such that $s_i' s_i = s_i \bmod q$; i.e., $s_i' = (q + s_i)/ s_i$. These are used as enabling keys to activate or revoke client decryption keys.
  - For each g_{nj} of C, TA generates corresponding $xbar_j = b^{-1}\, \Sigma x_i^n \bmod q$ ($i = 1, \ldots, n$, $i \neq j$) and $xhat_j = s'_j\, x_j^n$. Each tuple (p, $xbar_j$, $xhat_j$) ($j = 1, \ldots, n$) is a private client decryption key for the b group and can be activated and revoked independently of each other. The jth key is distributed to each member of the jth client subgroup by secure means.
  - TA determines which client subgroups are to be enabled and computes the product s of the associated s_j. Then it computes the server private encryption key $E = A^s$ mod p and public decryption keys $gbar = g^s \bmod p$ and $ghat = g^{sb} \bmod p$. The tuple (p, q, E, $gbar$, $ghat$) is distributed to the server group by secure means. All other data are private to the TA.

Mu-Varadharajan (MV) scheme



- TA generates MV parameters, group key, server key and client keys.
- TA transmits private encryption and public decryption keys to all servers using secure means.
- TA transmits individual private decryption keys to each client using secure means.
- TA can activate/deactivate individual client keys.
- The MV identity exchange is used to verify group membership.

Mu-Varadharajan (MV) identity scheme operations

- Client Alice verifies server Bob knows the secrets of the scheme identified with the *b* group and *j* subgroup.
  - Alice rolls random nonce *r* ($0 < r < q$) and sends to Bob.
  - Bob rolls random nonce *k* ($0 < k < q$) and computes $y = rE^k$, and public decryption keys $ybar = gbar^k$ and $yhat = ghat^k$, then sends (hash(*y*), *ybar*, *yhat*) to Alice.
  - Alice computes $F = ybar^{xhat}\, yhat^{xbar}$, which by construction is the inverse of E^k. She computes $x = rF^{-1}$, then verifies that hash(*x*) matches hash(*y*).
- As a practical consideration, this scheme is limited to *n* less than about 30 with *p* in the order of 500 significant bits. This is because the number of distinct primes s_j become harder to find as the number of significant bits of s_j diminish.

Key generation

- Key files are generated using the ntp_keygen utility.
  - Most files are generated and used on the same host; only the identity values need to be securely distributed in advance.
  - *hostname* is provided by the Unix gethostname() routine.
  - *filestamp* is the NTP seconds when the file was created.
  - All files are in PEM-encoded printable ASCII suitable as MIME extensions
- ntpkey_key_*hostname.filestamp*
  - Public/private encryption key
- ntpkey_cert_*hostname*.*filestamp*
  - X.509 version 3 certificate
- ntpkey_sign_*hostname*.*filestamp*
  - Public/private signature key; must agree with certificate key
- ntpkey_*scheme_hostname*.*filestamp*
  - Identification *scheme* IFF, GQ or MV

Key management

- Keyspace is relatively small, so keys must be refreshed frequently
  - Keys are refreshed automatically and without management intervention
  - Session key list is regenerated about once per hour
  - Server private cookie is regenerated about once per day
  - Public keys and certificates are regenerated by scripts about once per month
  - Autokey protocol automatically handles key refreshment and recovery
- Autokey protocol enforces partial ordering for file creation and use
  - NTP timestamp is appended to the name of every cryptographic data file
  - Filestamps accompany the data as it is moved from place to place
  - Certificate and certificate requests include filestamp as sequence number
  - Dependency graph is created for public keys, certificates and data dependent on them
  - By induction, the graph includes all cryptographic data in the network derived from the trusted primary servers at the root of the graph

Further information

- Network Time Protocol (NTP): http://www.ntp.org/
  - Current NTP Version 3 and 4 software and documentation
  - FAQ and links to other sources and interesting places
- David L. Mills: http://www.eecis.udel.edu/~mills
  - Papers, reports and memoranda in PostScript and PDF formats
  - Briefings in HTML, PostScript, PowerPoint and PDF formats
  - Collaboration resources hardware, software and documentation
  - Songs, photo galleries and after-dinner speech scripts
- FTP server ftp.udel.edu (`pub/ntp` directory)
  - Current NTP Version 3 and 4 software and documentation repository
  - Collaboration resources repository
- Related project descriptions and briefings
  - See “Current Research Project Descriptions and Briefings” at http://www.eecis.udel.edu/~mills/status.htm