EXPERIENCES IN THE FORMAL ANALYSIS OF THE GDOI PROTOCOL

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MOTIVATION AND BACKGROUND

- Project started in 1999
- At that time, had long history of formal analysis of crypto protocols (about 20 years, starting with Dolev and Yao work)
- Applied to lots of different types of problems
- Has had some real success
  - **Found previously undiscovered problems**
- But (as of 1999) -- lack of impact on "real life" protocols
  - **Few examples to point to of formal analysis affecting fielded product**
- WHY?
- In this project, attempted to address this problem

OUR PLAN

- Work closely with standards developers as they draft standard
  - **Give feedback as early in the standardization process as possible**
- Discuss any problems we found as they arose
  - **Allowed us to identify quickly which were real problems and which arose from misunderstanding of protocol**
- Recommend fixes when appropriate

GROUP WE WORKED WITH

- Internet Engineering Task Force (IETF)
  - **Mostly volunteer standards group responsible for internet protocol standards**
  - **Made up of different working groups concentrating on standards for different protocols**
- Internet Research Task Force (IRTF)
  - **Research group attached to IETF**
  - **Works on focussed research problems of interest to IETF**
- Secure Multicast Working Group (SMuG) in IRTF
  - **Devoted to protocols associated with secure multicast**

WHAT I'LL TALK ABOUT TODAY

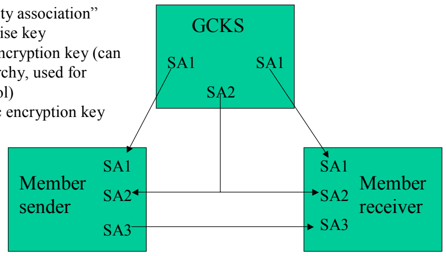
- How we worked with SMuG
- Protocol we worked on, GDOI
- A little background of formal methods for crypto protocol analysis
- Tool we used, NRL Protocol Analyzer
- Technical challenges we faced
- The outcome so far
- A coda

HOW WE WORKED WITH SMUG

- Attended SMuG meetings regularly
  - **Helped to**
    - Get to know SMuG members
    - Learn about background of SMuG protocols
    - Inform SMuG members of our own requirements
- Early on, picked Group Domain of Interpretation (GDOI) protocol as a good candidate
- Used GDOI drafts as basis for formal specifications as they came out
- When found problems or ambiguities, would discuss them with authors
  - **Would often lead to new GDOI drafts**

MULTICAST ARCHITECTURE USED BY GDOI

SA = "security association"
SA1 = pairwise key
SA2 = key encryption key (can be key hierarchy, used for access control)
SA3 = traffic encryption key



GDOI

- Protocol facilitating distribution of group keys by Group Key Distribution Center (GCKS)
  - **Embodies SMuG framework and architecture**
- Based on ISAKMP and IKE
  - **Standards developed for key exchange**
- Protocol uses
  - **IKE to distribute Category-1 SAs (pairwise keys)**
  - **Groupkey Pull Protocol initiated by member to distribute Category-2 SAs (KEKs)**
    - May also distribute Category-3 Sas (TEKs)
  - **Groupkey push Datagram to distribute Category-2 and Category-3 SAs**

GDOI PROTOCOLS

Groupkey Pull Protocol

```
     Initiator (Member)                    Responder (GCKS)
    ------------------                    ----------------
    HDR*, HASH(1), Ni, ID     -->
                              <--     HDR*, HASH(2), Nr, SA
    HDR*, HASH(3) [, KE_I]    -->
       [,CERT] [,POP_I]
                              <--     HDR*, HASH(4), [KE_R,] SEQ,
                                        KD [,CERT] [,POP_R]
Hashes are computed as follows:

    HASH(1) = prf(SKEYID_a, M-ID | Ni | ID)
    HASH(2) = prf(SKEYID_a, M-ID | Ni_b | Nr | SA)
    HASH(3) = prf(SKEYID_a, M-ID | Ni_b | Nr_b [ | KE_I ] | POP_I)
    HASH(4) = prf(SKEYID_a, M-ID | Ni_b | Nr_b [ | KE_R ] | SEQ | KD | POP_R)
```

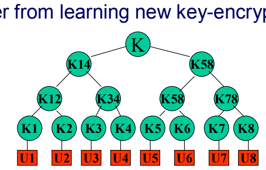
Groupkey Push Message

```
     Member                                GCKS or Delegate
    ------                                ----------------

                    <---- HDR*, SEQ, SA, KD, [CERT,] SIG
```

KEY HIERARCHIES FOR ACCESS CONTROL

- Key hierarchies can be used to prevent expelled member from learning new key-encryption keys



- Initially, each user gets all keys in its path to K
  - **When u1 leaves, GCKS computes new k12', k14',K'**
  - **U2 gets k2[k12'], k12'[k14'], k14'[K']**
  - **U3 gets k34[K14'], k14'[K']**
- GDOI does not specify key hierarchies but is compatible with them

THE NRL PROTOCOL ANALYZER

- Formal methods tool for verifying security properties of crypto protocols and finding attacks
- User specifies protocol in terms of communicating state machines communicating by use of a medium controlled by a hostile intruder
- User verifies protocol by
  1. **Proving a set of lemmas to limit size of search space**
  2. **Specifying an insecure state**
  3. **Using NPA to search backwards from that state to see if attack can be found**

NRL Protocol Analyzer Model

- Honest Principals modeled as communicating state machines
- Dolev-Yao Adversary
- Dishonest principals part of the adversary
- Each run of a protocol local to a principal assigned a unique round number
  - **Allows distinguishing of different runs local to a principal**

NPA Events

- Each state transition in an NPA spec may be assigned an event, denoted by

  event(P, Q, T, L, N)

  - **P: principal doing the transition**
  - **Q: set of other parties involved in transition**
  - **T: name of the transition rule**
  - **L: set of words relevant to transition**
  - **N: local round number**
- Events are the building blocks of the NPATRL Language

NPATRL

- NRL-Protocol-Analyzer-Temporal-Requirements-Language
  - **Pronounced 'N Patrol'**
- Requirements characterized in terms of event statements
- learn events indicate acquisition of information by adversary
- Syntax closely corresponds to NPA language, e.g.,

  receive(A, B, [message], N)
- Add usual logical connectives, e.g., ¬, ∧, =>
- One temporal operator ◇ meaning "happens before"

Example NPATRL Requirement

- If an honest A accepts a key Key for communicating with an honest B, then a server must have generated and sent the key for an honest A and an honest B to use.

accept(user(A, honest), user(B, X), [Key], N?) =>
◇send(server, (user(A, honest), user(B,honest), [Key], N?)

THREE TYPES OF REQUIREMENTS

- Secrecy requirements
  - **Intruder should not learn secrets, except under certain failure conditions**
- Authentication requirements
  - **If A accepts a message as coming from B intended for purpose X, then B should have sent that message to A and intended it for purpose X**
- Freshness requirements
  - **Conditions on recency and/or uniqueness of accepted messages**
- Some models bundle freshness and authentication together

Analysis Using NPA/NPATRL

- Map event statements to events in an NRL Protocol Analyzer specification
  - **Interpret atomic formulae**
- Take negation of each NPATRL requirement
  - **Defines a state that should be unreachable iff requirement is satisfied**
- Use NPA to prove goal is unreachable, or
  Use NPA to reach goal, i.e., find attack

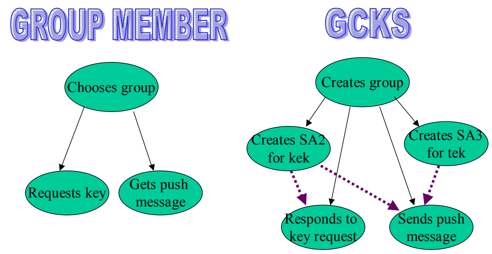
Existing NPATRL Requirements Suites

- Requirements have been given for
  - **Two party key distribution protocols**
  - **Two party key agreement protocols**
  - **Credit card payment transactions**
    - SET (Secure Electronic Transactions)

NPA SPEC OF GDOI

- Protocol starts with GCKS creating a group and a group key
- At any time after that, a group member may request to join the group by initiating a Groupkey Pull Exchange
  - **GCKS responds by completing protocol**
- At any time after that any of the below may occur
  - **GCKS may expel member and refuse to send it new keys**
  - **Group member may initiate new Phase 2 exchange**
  - **GCKS may send keys to group member using Groupkey Push Datagram**
- Initial spec took a little under a week to write

STRUCTURE OF SPECIFICATION



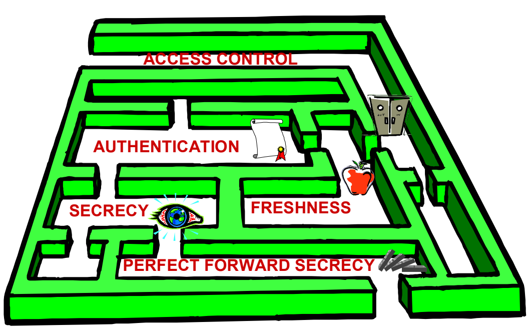
HOW SPECIFICATION LIMITED

- NPA can't currently handle unbounded data structures such as key hierarchies
  - **Can specify them, but they will send NPA into infinite loop**
  - **Currently investigating appropriate abstractions**
- So --
  - **For the moment did not try to specify key hierarchies, assumed each KEK is a single key**
  - **Assumed that in Phase 2 Exchange, one SAK sent**
  - **Assumed three possibilities for Groupkey Push Datagram**
    - One SAK or one SAT
- Also, did not include spec of IKE Phase 1

Challenges In Developing Requirements for Group Protocols

- In pairwise protocols, have notion of a *session*
  - **Secrecy means keys not learned by parties not involved in the session**
  - **Freshness means key is unique to a session**
- In group protocol session much more open ended
  - **Many keys may be distributed in one session**
  - **Principals may join and leave the group during a session**
    - How should their access to keys be limited?
    - How do different secrecy requirements interact with each other?

A MAZE OF REQUIREMENTS



FRESHNESS ISSUES

- Like secrecy, freshness is more complicated for group protocols
  - **Can no longer tie key to session**
- For GDOI, identified two types of freshness
  - **Recency Freshness**
    - KEK generated most recently (or after a specific time) is the current one
  - **Sequential Freshness**
    - Principal should never accept KEK that is less recent than the one it has
- For Groupkey push datagram, can only ensure that key principal accepts is most recent known to it, not that it is current

RECENCY FRESHNESS FOR PULL PROTOCOL

member_acceptpullkey(N,GCKS,(G,K,PK),N) =>
stealpairwisekey(env,(),(GCKS,M,PK),N?) or
not($\Diamond$ (member_requestkey(M,(GCKS,Nonce,PK),N) and
$\Diamond$ gcks_expire(GCKS,(),(G,K),N?)))

if member accepts key K via a pull protocol, then either
1. his pairwise key was stolen, or
2. K should not have expired previously to the request

can't require that key be current at time of receipt, could have expired en route

SEQUENTIAL FRESHNESS FOR PULL PROTOCOL

Member_acceptpullkey(M,GCKS,(G,K,PK),N?) =>
stealpairwisekey(env,(),(GCKS,M,PK),N?) or
not $\Diamond$ member_acceptkey(M,GCKS,(G,K1),N?) &
$\Diamond$ (gcks_makecurrent(GCKS,(),(G,K1),N?)
& $\Diamond$
gcks_makecurrent(GCKS,(),(G,K),N?)))

If member accepts a key K, then either
1. his pairwise key was stolen, or
2. he should not have previously accepted a key that became current later than K

SECRECY REQUIREMENTS FOR GDOI

- Forward access control
  - **Principals should not learn keys distributed after they leave the group**
- Backward access control
  - **Principals should not learn keys that expired before they joined the group**
- Perfect forward secrecy
  - **If pairwise key stolen, only keys distributed with that key after the event should be compromised**
- Other requirements may govern effects of stealing key encryption keys, etc.
- How do these interact with each other?

SOLUTION: DEVELOP CALCULUS OF SECRECY REQUIREMENTS

- Build collection of NPATRL statements of events that can lead to key compromise
  - **Currently restricted to requirements for keks**
  - **Five non-recursive base cases describing**
    - Stealing of pairwise and group keys
    - Group keys sent to dishonest members
  - **Two recursively defined cases addressing generalizations of forward and backward access control**
- Mix and match statements to get requirement of your choice

AN UNEXPECTED DEVELOPMENT

- All requirements could easily be expressed in terms of fault trees
  - **Described sequences of events that should or should not lead up to event such as accepting a key, learning a key,etc.**
  - **Can reason about sequences that**
    - Should both happen (AND)
    - One of which should happened (OR)
    - Should not happen (NOT)

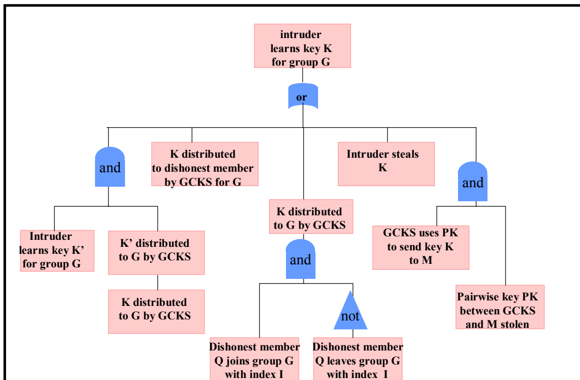


Fig. 4 Forward Access Control Without PFS or Backward Access Control

SOME RESULTS OF SPECIFYING PROTOCOL

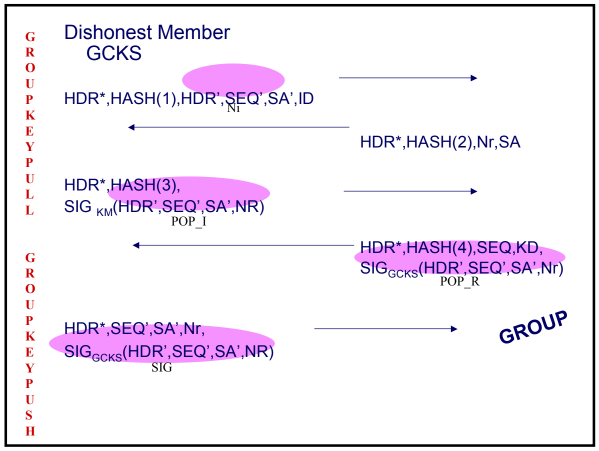
- Identified several omissions and ambiguities
- Found one major inconsistency
  - **Sequence numbers were originally send in KD payload**
  - **Sequence numbers updated every time new KEK created**
  - **Didn't account for fact that some push messages may not contain KEK's**
- Now sequence numbers updated every time new push message sent

SOME RESULTS OF SPECIFYING REQUIREMENTS

- Improvement to Proof-of-possession option
  - **In old version, principals only signed own nonces**
  - **Didn't work if pairwise keys compromised**
  - **Now, principals sign hash of both nonces**
- Found detail that needed to be added to Groupkey Pull protocol
  - **Did not satisfy sequential freshness unless require that member checks that SEQ number received in last message was greater than SEQ number it may currently hold**

RESULTS OF ANALYSIS

- Two similar oracle attacks making use of type confusion
- One found using NPA
- Another (simpler) one found after NPA found first attack
  - **Suggested by NPA result**
- Will present simpler attack here
- Suppose dishonest group member wants to trick other group members into accepting a fake key as a genuine one
- Suppose that protocol uses Proof-of-Possession option
- Then …



FIX TO PROTOCOL

- First, did quick analysis to see if attack was really possible
  - **What kind of assumptions about lengths of data did it require?**
- Whenever signature taken, prepend to signed data a tag saying what kind of signature it is
  - **GCKS pop**
  - **Member pop**
  - **Groupkey push**

RESULTS

- Identified potential GDOI problems early on, resulting in a better protocol
- Formal analysis credited with speeding up acceptance of GDOI and of the new MSeC (multicast security) working group formed out of SMuG
- Starting to see interest from other parts of IETF in performing or applying formal analyses
- Some avenues for further research
  - **Fault tree representation of requirements**
  - **Algorithms for detecting type confusion/oracle attacks**

A CODA

Most Important Need

- NRL Protocol Analyzer, and other formal crypto protocol analysis tools, don't support incremental analysis well
  - **Even minor changes may require complete reverification**
  - **As a result did complete formal analysis of system at only one stage**
- What's needed is a verification method that
  - **Is consistent with methods used by protocol designers**
  - **Supports incremental verification**

LOGIC FORCRYPTO PROTOCOL ANALYSIS

- Work with Dusko Pavlovic, John Mitchell, Anupam Datta, Ante Derek
- Basic idea:
  - **Axioms for deriving conclusions about protocol traces from messages received by principals**
    - E.g: If A sends a challenge, to B, and gets an authenticated response from B, then A knows that B responded after A's challenge
  - **Logic provides means for composing proofs**
- Applying it to GDOI with Dusko Pavlovic
  - **Evaluating logic as we apply it**
  - **Using feedback from GDOI analysis to extend and improve it**
  - **Also doing this for Kerberos**

GDOI AND POP AGAIN

- Recall that certificates *may* be used to disbribute public key certificates in GDOI
- Proof of possession uses challenge-response to prove that you actually know the private key
  - **Same nonces used for PoP as for challenge-response in core GDOI**
- Language in current version of GDOI seems to indicates that certificates can be used to distribute new identities as well

There are two alternative means for authorizing the GROUPKEY-PULL message. First, the Phase 1 identity can be used to authorize the Phase 2 (GROUPKEY-PULL) request for a group key. Second, a new identity can be passed in the GROUPKEY-PULL request. The new identity could be specific to the group and use a certificate that is signed by the group owner to identify the holder as an authorized group member. The Proof-of-Possession payload validates that the holder possesses the secret key associated with the Phase 2 identity.

- What can you prove from PoP in that case?

ATTEMPTED TO DERIVE PROOF

- Able to link request for key to Phase 1 identities
  - **Showed that request for key came from possessor of phase 1 identity**
- Able to link POP to identity in certificate
  - **Showed that POP showed that principal named in certificate is in possession of key**
- What we couldn't show:
  - **That there is any link between phase 1 identity and principal in certificate!**
  - **Because there isn't any!**

AN ATTACK

Suppose that I is a GCKS that wants join a group managed by another GCKS, B.
Suppose that I doesn't have the proper credentials to join B's group.
Then I can trick a member A who does into supplying them, as follows.

1. A --> I : HDR*, HASH(1), Ni, ID A requests to join I's group, sending a nonce Ni

1.' I_member --> B : HDR*, HASH(1)', Ni, ID' I requests to join B's group, forwarding A's nonce Ni

2.' B --> I_member : HDR*, HASH(2), Nr', SA' B responds to I with its nonce Nr'

2. I --> A : HDR*, HASH(2)', Nr', SA I responds to member A, but using B's nonce Nr'

3. A --> I: HDR*, HASH(3), CERT(for A's ID in group), POP = S_A(hash(Ni,Nr'))
A responds to I with a POP taken over A's and B's nonce

3.' I_member --> B: HDR*, HASH(3), CERT(for A's ID in group), POP = S_A(hash(Ni,Nr))
I as a member responds to B, using A's CERT and POP

4. B --> I_member : HDR*, HASH(4), KD
B sends keying information to I under impression the identity in A's certificate
belongs to I

CONCLUSION:
A VERIFIER'S WORK IS NEVER DONE