(In-)secure messaging with SCIMP and OMEMO

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Outline

Secure Messaging protocols

EFF ad in Wired magazine (source)

History of online secure messaging (1/2)

- 1991: Phil Zimmermann creates PGP
- 2004: Nikita Borisov, Ian Goldberg and Eric Brewer create OTR
  - Secure, but requires synchronous environment
- 2011: Gary Belvin introduces SecureSMS (master's thesis)
- 2012: SCIMP (Silent Circle instant messaging protocol)
  - By Vinnie Moscaritolo, Gary Belvin and Phil Zimmermann
  - SecureSMS for XMPP
  - Even copies variable names and equation numbering from Belvin's thesis (despite creating internal inconsistencies)
- February 2014: Open Whisper Systems releases TextSecure v2
  - Allows offline initial user message
  - Later renamed to Signal

History of online secure messaging (2/2)

- May 2014: SC updates to SCIMP v2
  - Allows offline initial user message
- August 2015: SC releases code for SCIMP v2
  - Adds more inconsistencies between code and documentation
- September 2015: SC discontinues SCIMP, switches to Signal based protocol
- October 2015: Andreas Straub proposes OMEMO
  - Multi-device Signal for XMPP
- Oct-Nov 2016: Trevor Perrin and Moxie Marlinspike release official specification for the Signal protocol
- Dec 7th 2016: OMEMO gets standardized by the XMPP Standard Foundation: XEP-0384 (experimental)

My involvement

- December 2015: My Master's thesis (at TU/e) on SCIMP
  - SCIMP v1 is formally verified by ProVerif to be secure
  - SCIMP v2 contains cryptographic flaws
  - the implementation contains many security bugs
- June 2016: My cryptographic report on OMEMO
  - Minor bug found in multidevice setting
    - Developer patches it the same day as reported
- July 2016: Tanja Lange and I release SCIMP preprint paper
  - Some of Silent Circle's code (copied from SCIMP implementation) still contains bugs that were reported in my thesis
    - Bugs got patched a few days later
    - Initial bug report: **September 2015**

Formal verification

- Create a mathematical model of a program
- Ask the computer to prove several theorems about the program. For example:
  - correctness
  - confidentiality of data/keys
  - authenticity of messages

Formal verification

A successful formal verification is *not* a guarantee that the implementation is secure:

- The model might not accurately describe the implementation
  - Model often needs to be a simplification of the code
  - Code evolves
- The attacker model might not be strong enough
  - For example, the attacker might implement a side-channel attack
- The context in which the model is deployed might break model assumptions

Formal verification

So why do we still go through the trouble?

- Unsuccesful formal verification reveals bugs!
- Building the model itself exposes many bugs and omissions
- The model exposes assumptions that would remain implicit in specs/code
- Successful verification adds trust in protocol by eliminating possibility of a large class of vulnerabilities

ProVerif

- Formal language for modelling interactive protocols
  - Requires a model for attacker capabilities
    - ProVerif uses Dolev-Yao: attacker has full control over the network
- Limited computing power: have to break up the protocol in pieces
  - We have to manually prove that their composition is still secure
- No memory model
  - But there are some tricks to model key erasure/future secrecy
  - Requires manual "proof" that sequential composition is still secure

ProVerif

- ProVerif has limited available primitives
- We can define the required primitives using standard "tricks"
- For example, to create an authenticated channel:
  - Create a private channel (confidential and authentic)
  - Create a process that runs in parallel with the main process. Publish everything that is communicated on this channel in a public channel
- Pro: we can model the protocol very accurately
- Con: requires expertise to implement the correct primitive
- Con: the added complexity makes it very computationally intensive to prove security

ProVerif example

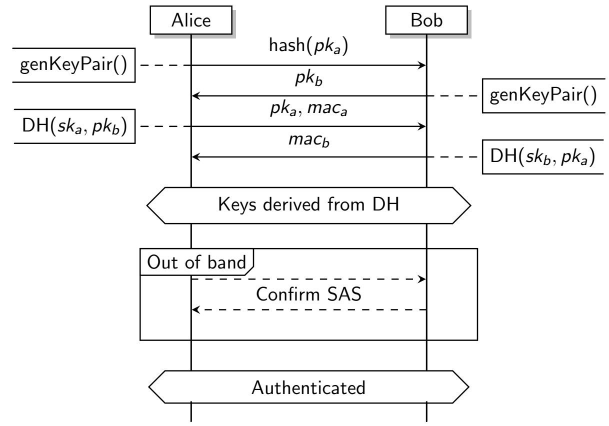
```
(*** Main ***)

process
  (* Allow arbitrary many protocol runs *)
  !
  (* Let the adversary decide who will engage in key negotation *)
  in(ch, (init:identity, resp:identity));
  (* Create a new phone channel *)
  new phone : channel;
  (* Allow eavesdropping on the phone channel *)
  (! in(phone, x:bitstring); out(ch, x)) |

  if init = Compromised then (
    out(ch, phone);
    processResponder(init, resp, phone)
  ) else if resp = Compromised then (
    out(ch, phone);
    processInitiator(init, resp, phone)
  ) else (
    processInitiator(init, resp, phone) |
    processResponder(init, resp, phone)
  )
```

ProVerif for SCIMP

Security properties we expect of SCIMP and how to prove them with ProVerif:

- **confidentiality**: can an adversary can learn private keys/messages?
- **authenticity/integrity**: can an adversary trigger the "user-accepts" event?
- **forward secrecy**: leak an updated key, then check confidentiality of old messages/keys
- **future secrecy**: publish all key material, then run a key negotiation over a private channel and check confidentiality
- **deniability**: run the protocol with the honest user and with the adversary, then check if the transcripts are indistinguishable

SCIMP v1: Key negotiation

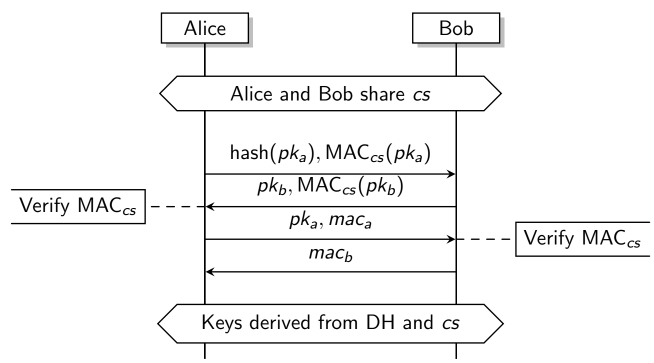


SAS: short authentication string

SCIMP v1: Key negotiation

- ECDHE gives shared secret Z, from which are derived:
  - $k_{snd,0}, k_{rcv,0}, i_{snd,0}, i_{rcv,0}$; for message encryption and authentication
  - mac_a, mac_b; to confirm knowledge of Z
  - SAS; for authentication of identity
  - *cs*; for rekeying
- User messages can be sent after four key exchange messages
- SAS confirms identity all previous communication
  - Requires commitment to pk_a to prevent collision attack

SCIMP v1: Rekeying



SCIMP v1: Rekeying

- First: store old decryption key (messages might arrive out of order)
- Optional: SAS comparison only after several rekeyings
- Rekeying ensures *future secrecy*
- It is not specified when to rekey
- Protocol aborts on error

SCIMP v1: Sending user messages

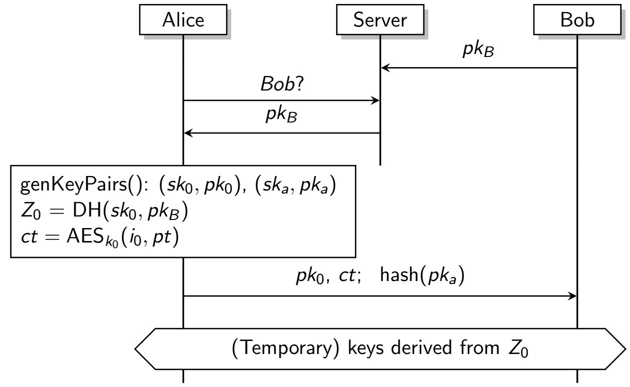
- Encrypt
  - ciphertext $= \text{AES}_{k_j}(i_j,\text{plaintext})$
- Update keys (ratchet)
  - $k_{j+1} = \text{MAC}_{k_j}(i_j)$
  - $i_{j+1} = i_j + 1$
- Send message:
  - i_j
  - ciphertext

- No message signatures: deniable
- Ratchet enables key erasure, but:
  - Out of order messages require you to store old keys
  - Old keys compromise future keys

Proverif results for SCIMP v1

- First key negotiation (**if** SAS confirmed over authenticated channel)
  - ✓ Confidentiality of keys
  - ✓ Authenticity of keys and other party identity
- Rekeying
  - ✓ Confidentiality of keys
  - ✓ Authenticity of keys and other party identity
  - Future secrecy
    - ✓ When attacker misses first rekeying after compromise
    - ✓ When users reconfirm the SAS
- Sending user message
  - ✓ Confidentiality of keys
  - ✓ Strong secrecy of messages
  - ✓ Authenticity of messages and keys
  - ✓ Forward secrecy (**if** keys can be erased)
  - ✓ Deniability

SCIMP v2: Progressive encryption



- From here on: regular key negotiation in parallel to user messages

Proverif results for SCIMP v2

- Progressive encryption
  - × Confidentiality/authenticity of first message
  - ✓ Confidentiality/authenticity of all messages and keys (**after** SAS)

SCIMP

- ProVerif reports that the initial message of SCIMP v2 is not confidential
  - This does not impact SCIMP v1
- But, ProVerif also verifies that users can detect this when confirming the SAS later
- To determine the impact of this vulnerability, we had to look at the source code

SCIMP

SCIMP

A short example to give a flavor of the code

```
unsigned long ctxStrLen = 0;
size_t kdkLen;
int keyLen = scSCimpCipherBits(ctx->cipherSuite);
```

- **ctxStrLen** length in bytes (computing function returns size_t)
- **kdkLen** length in bytes
- **keyLen** function name suggests bit-length, but k_{snd} is $2 * \textbf{keyLen}$ bits long

SCIMP

- Each message has a plaintext tag identifying the type:
  - keying message; or
  - user message
- The adversary can block the key negotiation using just this tag, thereby having set up a succesful MitM
- The vigilant user might detect this
- But the code contains another bug: the receiver overreacts when a keying message is received out of order
  - only the message tag is inspected
  - the receiver deletes all local key material
  - thereby annulling any security set up in the past
- The adversary can desynchronize any secure session with a single out-of-order key message and set up a MitM undetected

OMEMO

https://conversations.im/omemo/

https://radicallyopensecurity.com/
https://pacificresearchalliance.com/

Multi-device Signal

https://whispersystems.org/

Shares the private key between multiple devices[2]

1. Generate ephemeral Signal key-pair on desktop
2. Scan public key with phone (using QR-code)
3. Set up Signal session between phone and desktop
4. Send phone's private-key to desktop
5. Replace desktop ephemeral key with the received private key

[2]Limited to one smartphone and a desktop app

Multi-device OMEMO (flawed)

- Each device has its own private key
- Each pair of devices sets up a Signal session
- A user message gets authenticated-encrypted with a random key
- The ciphertext and tag are sent to each receiving device
- The random key is sent to each user inside the Signal session

Multi-device OMEMO (flawed)

One malicious device breaks authenticity of all messages in the conversation

- Assume Eve convinces Alice that her device belongs to Bob
- Eve could intercept any message by Alice...
- ...get the random key that Alice sent her...
- ...encrypt her own message using the same key...
- ...and send it to Bob, who thinks it came from Alice.

Multi-device OMEMO (fixed)

- Each device has its own private key
- Each pair of devices sets up a Signal session
- A user message gets authenticated-encrypted with a random key
- The ciphertext and tag are sent to each receiving device
- The random key **and tag** are sent to each user inside the Signal session

Conclusions

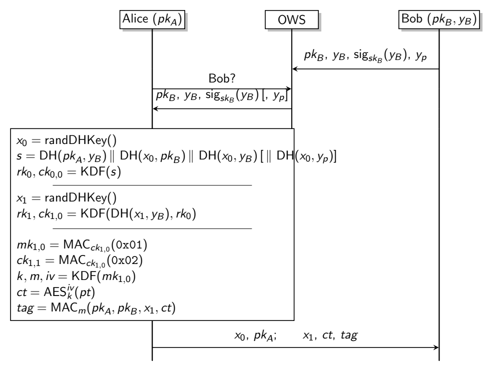
- Implementing crypto protocols is hard
  - Even experienced cryptographers get it wrong sometimes
- Despite all the shortcomings of ProVerif, the tool did help me analyze the protocol and expose flaws
  - I would love to see more powerful and easier to use tools
  - if possible: a tool that extracts the model from the code
- For those who just want painfree secure messaging: use Signal
  - with OMEMO, that no longer means that you are tied to the Signal *application* and *server*
    - set up your own compatible XMPP server (or create an account at an existing one)

Thank you

Further reading

- These slides will be available on my website: https://www.zeroknowledge.me/
- ProVerif models are available: https://github.com/sebastianv89/scimp-proverif
- My thesis about SCIMP: http://repository.tue.nl/844313
- Preprint about SCIMP (with Tanja Lange): https://eprint.iacr.org/2016/703
- Get Signal (Android/iPhone): https://whispersystems.org/
- Try OMEMO (on Android): https://conversations.im/
- OMEMO audit report: https://conversations.im/omemo/audit.pdf

Signal



More on SCIMP

Other discrepancies between the model and the implementation

- Group messages have a single symmetric key
  - Relies on trust in the SC server
  - Subject to a trivial MitM attack
- CCM-mode implementation did not validate authentication tags
  - Problem in LibTomCrypt (fixed)
- Code contains many timing side-channel vulnerabilities
- The message parsing queue has a race condition
- Unchecked function error codes
  - Including memory allocations
- State machine based design: good coding style
  - and helps in making a model of the code
  - in case of SCIMP: helps find where specs and code differ

More on SCIMP file transfer

- Convergent encryption
  - key = hash(file)
    - send as SCIMP message
  - ciphertext = $\text{AES\_CCM}_{key}(\text{file})$
    - upload to cloud
- Known vulnerabilities of CE:
  - confirmation of a file
  - learn the remaining information
- SC: receiver does not check hash(file) = key
  - file injection attack
  - This attack remained in the code until July, when we looked at the updated code again