HUNTING FOR VULNERABILITIES IN SIGNAL - HITBSECCONF2017 AMSTERDAM

JP Aumasson & Markus Vervier
WHOIS

• **Markus** (@marver)
  - Head of research @ x41 D-Sec
  - Speaks German
  - Not CISSP

• **JP** (@veorq)
  - Principal researcher @ Kudelski Security
  - Speaks French
  - Crypto guy
PROPS

• This BH US 2016 boring talk
• Open Whisper Systems
• Eric Sesterhenn
• Hanno Boeck
AGENDA

- **Signal** internals, security promises
- **Attack** surface and liabilities
- **Bugs, alternative features**, and demos
- Conclusions
SIGNAL

Open Whisper Systems
THE SIGNAL APPS

- Mobile apps for **messaging** & audio/video **calls**
- By Open Whisper Systems (Moxie Marlinspike et al.)
- Formerly known as "TextSecure", "RedPhone"
- Android, iOS, and Chrome Desktop app
TRUSTED TOOL

- Endorsed by Snowden and other opinion leaders
- Popular among activists in the US and abroad
- Minimal data collection from Signal servers

Attachment A

<table>
<thead>
<tr>
<th>Account</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Last connection date: Unix millis</td>
</tr>
<tr>
<td></td>
<td>Account created: Unix millis</td>
</tr>
</tbody>
</table>
SECURITY PROMISES

- Solid *end-to-end encryption*, defending against
  - Active network attackers
  - Client and server compromises
  - Traffic analysis (partially)
- High assurance *software*, with
  - Code perceived as high-quality
  - No major security issue ever
  - Reproducible Android builds
SIGNAL IS MORE THAN SIGNAL

Core crypto "libsignal" licensed to and integrated in

- Facebook Messenger's "Secret Conversations" mode
- Facebook WhatsApp default encryption
- Google Allo's "Incognito" mode

SECRET CONVERSATIONS relies upon the Signal Protocol. Messenger uses Signal Protocol’s implementation as available in the open-source libsignal-protocol-java and libsignal-protocol-c libraries for Android and iOS respectively. Secret Conversations also incorporates new abuse-reporting features which are not present other platforms which can be detected and removed.


Your personal files are encrypted!
KEY AGREEMENT: X3DH

- Combines 4 key pairs: long-term and ephemeral
- One-time *prekeys* trick, to simulate online-ness
- *Forward-secret*, resilient to malicious servers
- *Out-of-band* identity verification necessary
SESSION KEYS: DOUBLE RATCHET

Protocol to compute message-unique keys:

- New Diffie-Hellman for every first message from a party
- "Key := Hash(Key)" for consecutive messages
- Past and future messages safe if present key known
- Attachments have identical protection
THE "SIGNAL PROTOCOL"

= X3DH and double ratchet as implemented in Signal

We want to maintain "Signal" and "Signal Protocol" as names associated with up-to-date high-quality software, the latest protocol features, and all the specific choices that we've made in implementing these concepts. We've made those choices very carefully, we will continue to update them carefully, and we want people to have confidence they will benefit from that care when they see the word "Signal."

(Moxie Marlinspike, messaging@moderncrypto.org ML, 30.11.16)
WAIT – WAS THAT ALL?
a.k.a. "code is documentation":

- How are attachments encrypted?
- How are audio and video streams encrypted?
- Are they fully integrity checked?
- How does group messaging work?

etc.
NETWORK ARCHITECTURE

Attachments stored on S3, at e.g.
https://whispersystems-textsecure-attachments.s3.amazonaws.com

Messaging servers run by OWS
CODE BASE (CLIENT-SIDE)

Main repos from https://github.com/whisperSystems:

- libsignal-service-java (~20kloc Java)
- libsignal-protocol-java (~20kloc Java)
- Signal-Android (JNI + ~60kloc Java)
- libsignal-protocol-c (~30kloc C)
- SignalServiceKit (~20kloc Obj-C)
- Signal-iOS (~25kloc Obj-C)
Android App Software Stack

libssignal-service-java

org.whispersystems.libsignal
org.whispersystems.libsignal.devices
org.whispersystems.libsignal.ecc
org.whispersystems.libsignal.fingerprint
org.whispersystems.libsignal.groups
org.whispersystems.libsignal.groups.ratchet
org.whispersystems.libsignal.groups.state
org.whispersystems.libsignal.kdf
org.whispersystems.libsignal.logging
org.whispersystems.libsignal.protocol
org.whispersystems.libsignal.ratchet
org.whispersystems.libsignal.state
org.whispersystems.libsignal.state.impl
org.whispersystems.libsignal.util

libssignal-protocol-java

javax.crypto
java.security
Curve25519
PREVIOUS RESEARCH

No public record of major security bug

Minor security issues fixed (see tracker)

Formal analysis of the protocol (Cohn-Gordon et al.)

Key compromise impersonation, replay (Kobeissi et al.)
ATTACK SURFACE
THE NETWORK ATTACKER

- Goal: compromise secrecy, impersonate legit peer
- Can inject/modify messages within X3DH, double ratchet
- Can sabotage prekeys (invalid value or format, etc.)
THE MALICIOUS PEER

- **Goal:** own other peer(s)
- **Got keys,** can trigger/abuse parsing of text/media data
- More powerful than the network attacker
DEPENDENCIES

signal code.  third party code
THIRD-PARTY CODE

- **Android**: 500kloc of C etc. (WebRTC, OpenSSL)
- **iOS**: ~ 60kloc of Obj-C and C (speex codec, DSP, etc.)
- Both: OS components to decode images, low-level stuff
- Crypto: curve25519-donna.c, Java SDK crypto
MISSING MITIGATIONS AND INSECURE DEFAULTS

- No sandboxing on Android nor iOS
- Hardware keystore not used on Android
- Parsing of media files from untrusted sources
- Dependency on iOS/Android media libraries
MORE ATTACK SURFACE?

Signal and GIPHY
moxie0 on 01 Nov 2016

The latest Signal release for Android includes support for GIF search and browsing. Signal has long supported sending and receiving GIFs, but this is an experiment that allows users to browse, search, and select popular GIFs from within Signal.

Disappearing messages for Signal
moxie0 on 11 Oct 2016
USER RESPONSIBILITIES

Check fingerprints, don't jailbreak/root, OPSEC, etc.

If you wish to verify the security of your end-to-end encryption with Markus Vervier, compare the numbers above with the numbers on their device.
UNREALISTIC SECURITY MODEL?

"Break-in recovery" protects against an attacker that extracts temporary keys... but only certain keys:

- Security recovered if a "KDF key" leak
- **Recovery impossible** if a "root KDF key" leaks
  
  *(Can silently MitM, as Steve Thomas tweeted)*

  But keys are all in the same memory region...

  Does this model make any sense on mobile?
BUGS AND "FEATURES"
METHODOLOGY

Multi-level holistic approach to bug discovery:

- Machine learning-guided fuzzing
- Cloud-based parallel concolic execution
- State-machine meta-model formal verification
- Differential cryptanalysis using syscalls as side channels
- Blockchain smart contracts to record vulns found

(Releasing our tool, free for commercial use only)
ACTUAL METHODOLOGY

I HAVE NO IDEA WHAT I'M DOING
SERIOUSLY

No rigorous process
No automation or fuzzing
We only superficially reviewed:

- Obvious user input, protocol edge cases
- Common software bug classes
- **Client** code, *not server code*
- **Messaging** protocol/code, *not calling*
TOOLSET

iPhones, rooted Androids, Chrome extension

Signal service CLI [https://github.com/AsamK/signal-cli](https://github.com/AsamK/signal-cli)
*(to control what is sent to the server/peers)*

Python MitM'ing tools
MAC BYPASS (ANDROID)

```java
private void verifyMac(File file, Mac mac) throws FileNotFoundException, InvalidMacException {
  try {
    FileInputStream fin = new FileInputStream(file);
    int remainingData = Util.toIntExact(file.length()) - mac.getMacLength();
    byte[] buffer = new byte[4096];

    while (remainingData > 0) {
      int read = fin.read(buffer, 0, Math.min(buffer.length, remainingData));
      mac.update(buffer, 0, read);
      remainingData -= read;
    }
  }
}
```

- 64-bit (long) file.length() cast to 32-bit (int)
- file.length() = X + 4GB => remainingData = X
- MAC computed over first X bytes => extra 4GB can be set to arbitrary values and pass the MAC verification
MAC BYPASS: BASIC EXPLOITATION

MitM from S3, where attachments are stored:

- Await a request to fetch an attachment
- Pad the attachment with 4GB + use HTTP compression
- => Data attached to original data unnoticed
MAC BYPASS: MORE EXPLOITATION

Problem: decryption key is unknown, so can't forge meaningful ciphertext blocks.

Or can we? Exploit malleability of CBC mode

- CBC decryption: $P[i]=\text{Dec}(C[i]) \oplus P[i-1]$
- Know/guess one $\text{Dec}(C[i])$, choose $P[i-1]$
- Control every other plaintext block!
(Image stolen from another talk)
MAC BYPASS: DEMO

Blind message repetition

Playback isn’t supported on this device.
MAC BYPASS

Known plaintext forgery
NO PUBLIC KEY VALIDATION

ECDH: \text{private-key} \times \text{public-key} = \text{shared-secret}

- If \text{public-key} = 0, then \text{shared-secret} = 0
- Such invalid public keys should not be accepted
- Signal accepts \text{public-key} = 0
IMPACT OF INVALID KEYS

- You can force all peers to send you messages encrypted using an all-zero key (thus, essentially in clear text)
- Deniability ("PRNG bug!")
- Kills break-in recovery
C LIB CALLBACKS

C libsignal users need to define callbacks such as `encrypt_func()`, used to encrypt stuff (pretty important)

```c
int signal_encrypt(signal_context *context,
                   signal_buffer **output,
                   int cipher,
                   const uint8_t *key, size_t key_len,
                   const uint8_t *iv, size_t iv_len,
                   const uint8_t *plaintext, size_t plaintext_len)
{
    assert(context);
    assert(context->crypto_provider.encrypt_func);
    return context->crypto_provider.encrypt_func(
                   output, cipher, key, key_len, iv, iv_len,
                   plaintext, plaintext_len,
                   context->crypto_provider.user_data);
}
```
C LIB CALLBACKS

Unit tests provide example implementations, for example to use OpenSSL to encrypt stuff in encrypt_func()

```c
test_encrypt(signal_buffer **output, int cipher, const uint8_t *key, size_t key_len,
const uint8_t *iv, size_t iv_len, const uint8_t *plaintext, size_t plaintext_len,
void *user_data)
{
    int result = 0;
    uint8_t *out_buf = 0;

    const EVP_CIPHER *evp_cipher = aes_cipher(cipher, key_len);
    if(!evp_cipher) {
        fprintf(stderr, "invalid AES mode or key size: %zu\n", key_len);
        return SG_ERR_UNKNOWN;
    }
```
BUGS IN EXAMPLE CALLBACKS

Bugs in test_encrypt():

• Type confusion => crash for certain messages (64-bit)
• Integer overflow + potential heap overflow (32-bit)
RTP PACKETS UNDERFLOW

When packetLen < sizeof(RtpHeader), payloadLen is negative => out-of-bound read in HMAC

RtpPacket* RtpAudioReceiver::receive(char* encodedData, int encodedDataLen) {
    int received = recv(socketFd, encodedData, encodedDataLen, 0);

    if (received == -1) {
        __android_log_print(ANDROID_LOG_WARN, TAG, "recv() failed!");
        return NULL;
    }

    RtpPacket *packet = new RtpPacket(encodedData, received);
    ...

RtpPacket::RtpPacket(char* packetBuf, int packetLen) {
    packet = (char*)malloc(packetLen);
    // 1. INTEGER UNDERFLOW
    payloadLen = packetLen - sizeof(RtpHeader);
    memcpy(packet, packetBuf, packetLen);

    Seems unexploitable...
CRASHY IMAGES

• Signal uses libskia for media decoding
• Bugs in libskia...
• Can't disable media files parsing in Signal

What can wrong?
DEMO CRASH

Signal bootloop (reboot root-cause NOT in Signal)

Playback isn't supported on this device.
MESSAGE REPLAY
THE EVERLASTING PREKEY

- Key agreement uses **one-time** prekeys
- Except for the "**last-resort**" key
- Fallback mechanism against DoS

```java
package org.whispersystems.libsignal.util;

public class Medium {
    public static int MAX_VALUE = 0xFFFFFFFF;
}

public byte[] decrypt(PreKeySignalMessage ciphertext, DecryptionCallback callback)
    throws DuplicateMessageException, LegacyMessageException, InvalidMessageException,
            InvalidKeyIdException, InvalidKeyException, UntrustedIdentityException {
    ...  
        if (unsignedPreKeyId.isPresent()) {
            ...
```
X3DH KEY AGREEMENT

• Alice fetches Bob's id key and prekey from server...
• Computes shared secret, encrypts a message, sends with pubkeys...
• Bob computes shared secret, decrypts the message...
• Prekey removed from the server, except if it's the last resort key (after all prekeys have been used)
Message is a bundle of a *PreKeySignalMessage* and an encrypted message (*WhisperKeyMessage*)
PREKEY MESSAGE INTEGRITY

Only the encrypted part is integrity checked!
DEFENSES AGAINST REPLAY

• Bob *won't do* new key agreement for known base keys
  ▪ *Create fake session states and exhaust the state limit*

• A **valid ciphertext** is needed (with a valid MAC)
  ▪ *Piggyback on messages from a different session*
WHY REPLAY IS POSSIBLE

Key exchange and ciphertexts can be replayed because:

- Bob does not check if the encrypted message belongs to the prekey part of the message
- Prekey messages are not integrity checked, so a MiTM can create arbitrary session states
- Limit of 40 session states, old ones will be purged
HOW TO REPLAY

1. Exhaust Bob's prekeys (e.g. "evil backend" deletes normal prekeys)
2. Let Alice create a session with the last resort key
3. Record Alice's first message(s)
4. Replay! (even after Bob computes new prekeys)
REPLAY DEMO

```
$./signal_replay_attack 3
*** FINISHED SETUP ***
*** ALICE SESSION 1 ***
Alice: THIS SHOULD NEVER BE REPLAYED: Hey Bob, delete all data, will ya?
*** ALICE SESSION 2 ***
Alice: L'homme est condamné tre libre
*** CREATING 3 FAKE SESSIONS ***
*** tampering the original msg
[NOTICE] Bad MAC
[WARNING] Message mac not verified
Alice: sekret
*** tampering the original msg
[NOTICE] Bad MAC
[WARNING] Message mac not verified
Alice: sekret
*** tampering the original msg
[NOTICE] Bad MAC
[WARNING] Message mac not verified
Alice: sekret
*** REPLAYING MESSAGE FROM SESSION 1 3 TIMES***
[INFO] We've already setup a session for this V3 message, letting bug message fall through...
[NOTICE] Bad MAC
[WARNING] Message mac not verified
[NOTICE] Bad MAC
[WARNING] Message mac not verified
[NOTICE] Bad MAC
[WARNING] Message mac not verified
[NOTICE] Bad MAC
[WARNING] Message mac not verified
[WARNING] Received message with old counter: 1, 0
```

```
signal_replay_attack: signal_replay_attack.c:324: test_repeat: Assertion `result == 0' failed. Aborted
```
AUDIO FILE SERVER ON LOCALHOST

• If you play an audio file that was sent to you an open HTTP-Server is started on localhost
• Random 16 byte URI, random port
• Not a direct problem (unless port and URI info leaks)
MORE?

Looked at it yesterday morning... 😊

- Greater risk of "friendly fire" (© Justin)
- Can coerce peers into using \( K \equiv 0 \)
- ?
CONCLUSIONS

• Signal has a huge code base, underanalyzed
• Our work: Not an audit! It is not complete.
• Expecting more logic bugs, protocol edge cases, etc.
• Secure messengers need better mitigation and isolation.