The Candidate Key Protocol for Generating Secret Shared Keys from Similar Sensor Data Streams

ESAS 2007
2. July 2007, 09:00

Rene Mayrhofer
Lancaster University, UK

The scenario: spontaneous authentication

What do we already have?

Current approaches:

- Two (or multiple) phases
- Key agreement: typically select peer device + Diffie-Hellman
- Peer authentication: various options
  - commitment schemes
  - interlock-based protocols
- Verification based on some out-of-band channel
  - verification of key hashes: display+user+yes/no
  - transmission over secret and/or authentic channel: display+user+keypad, infrared, ultrasound, laser, display+camera, audio, NFC, ...
  - shared secret: common data, possibly "fuzzy"

Problem of scalability

Most current protocols scale linearly with number of potential neighbors

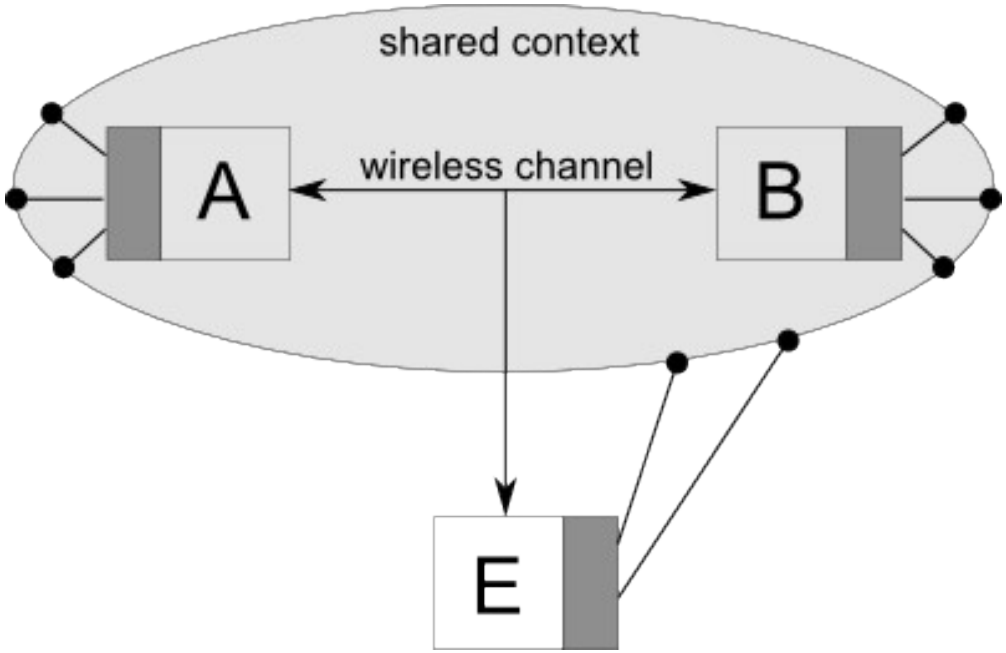
- already good in terms of network, CPU, power consumption, etc.
- but: user attention does not scale as well

User interaction is problematic

- explicit selection of network entity *or*
- only selection of physical entity with implicit binding to network entity
  ⇒ (slight) delay while multiple devices are tried

Better: constant-scalable interaction with broad-/multicast protocols

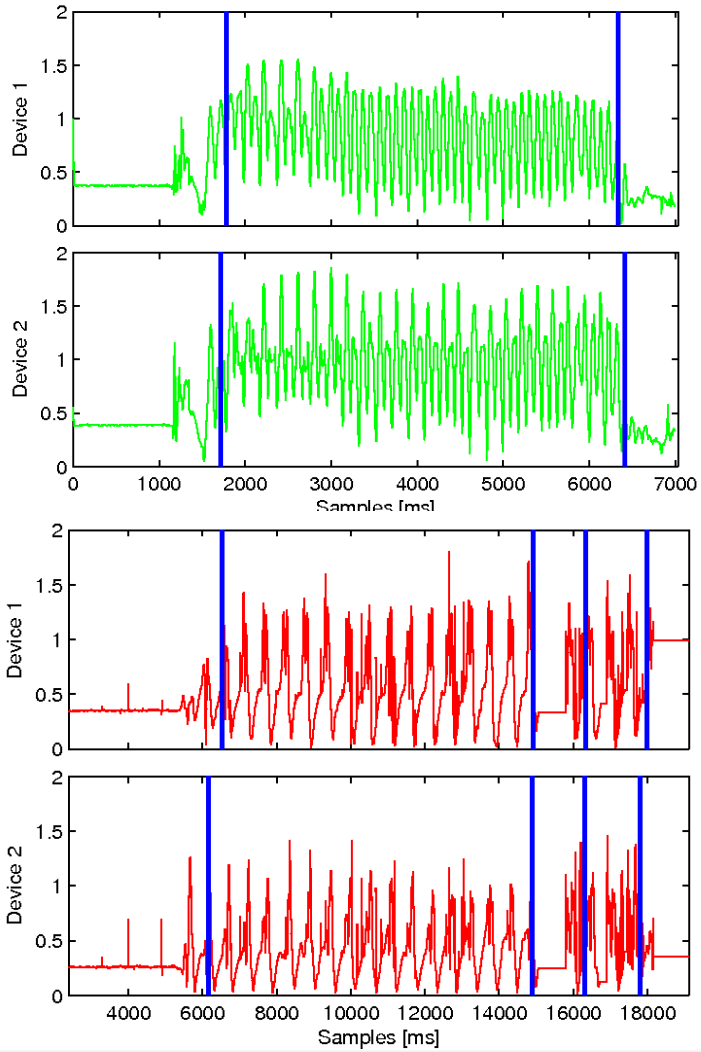
Context-based authentication



- main threat scenario: MITM on wireless communication channel
- intended communication partners A and B share some context
- attacker E has inferior access to this context
- respective aspect of context represented by sensor data streams
  ⇒ shared (weakly) secret information

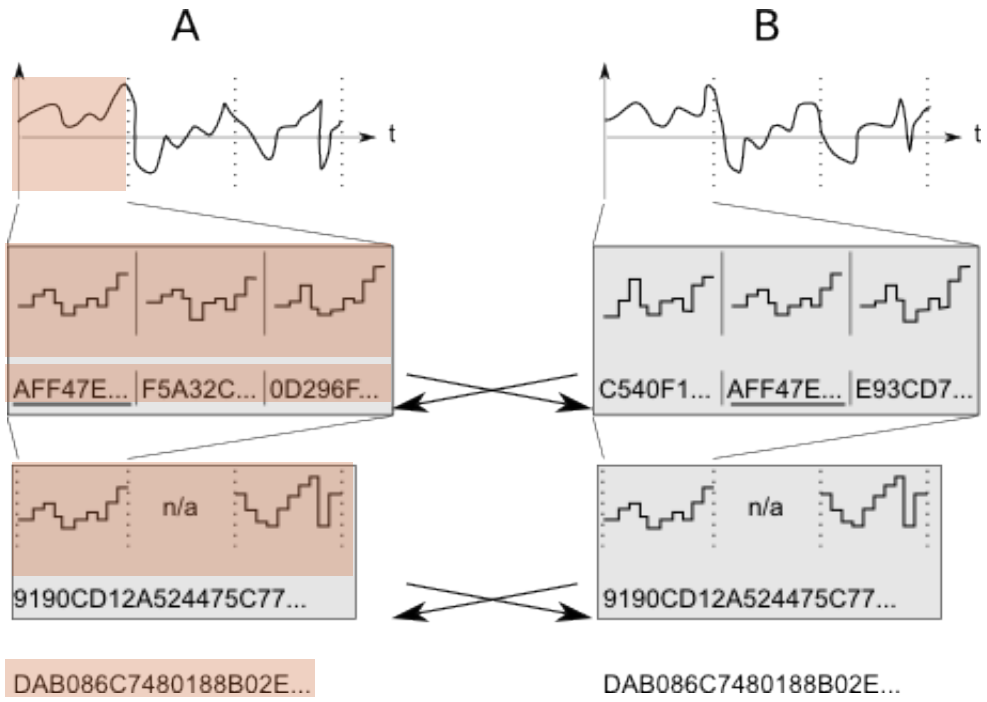
From sensor data to keys: first steps

1. Sensor data acquisition
   - potential problem: side-channel attacks
2. Temporal alignment
   - triggering
   - synchronization
3. Spatial alignment
   - when using multi-dimensional input data, these dimensions may be in different reference systems on different devices
4. Feature extraction
   - raw data usually unusable, domain-specific



The Candidate Key Protocol

1. features extracted from sensor data streams
   ⇒ multiple feature vectors, e.g. with different quantization offsets, different parameter sets, etc.
2. multiple candidate key parts for each time window,
   hashes are broadcast
3. multiple matching key parts concatenated to candidate keys,
   hashes are sent to respective host
4. when candidate key can be generated at receiving host, acknowledge and use as shared secret key



A bit more detail...

Alice	Message	**Bob**
I.1. New local feature vectors for rounds r_a, r_b		
For each vector v_a^i:		For each vector v_b^j:
$s_a^{r_a} \in 0, \ldots, 2^{128} - 1$	unique for each round	$s_b^{r_b} \in 0, \ldots, 2^{128} - 1$
$h_a^i := H(s_a \mid v_a^i)$		$h_b^j := H(s_b \mid v_b^j)$
add $< r_a, v_a^i >$ to LH_a		add $< r_b, v_b^j >$ to LH_b
I.2. Exchange candidates		
	CAND $C_a^{r_a} :=< r_a, s_a, h_a^1, h_a^2, \ldots >$ →	
	← CAND $C_b^{r_b} :=< r_b, s_b, h_b^1, h_b^2, \ldots >$	
$r_a := r_a + 1$		$r_b := r_b + 1$

global circular buffer

A bit more detail...

I.3. New remote candidates

For each hash $\widetilde{h}_b^j$:
if $\exists$ $<\widehat{r}_a, \widehat{v}_a^i> \in LH_a$
s.t. $\widetilde{h}_b^j = H(\widetilde{s}_b | \widehat{v}_a^i)$
then add j to $ML_a^{r_b}$
and add $< \widehat{r}_a, \widehat{v}_a^i >$ to $MC_{a,b}$

remember *remote* round/candidate numbers

specific to remote host

For each hash $\widetilde{h}_a^i$:
$\exists$ $<\widehat{r}_b, \widehat{v}_b^j> \in LH_b$
s.t. $\widetilde{h}_a^i = H(\widetilde{s}_a | \widehat{v}_b^j)$
then add i to $ML_b^{r_a}$
and add $< \widehat{r}_b, \widehat{v}_b^j >$ to $MC_{b,a}$

I.4. (optional) Exchange matches

only for asymmetrical settings

MATCH $M_a^{r_a} :=< \widetilde{r}_b, ML_a^{r_b} >$ →

MATCH $M_b^{r_b} :=< \widetilde{r}_a, ML_b^{r_a} >$ ←

add numbers $\widetilde{ML}_b^{r_a}$ of round $\widetilde{r}_a$ from LH_a to $MC_{a,b}$

add numbers $\widetilde{ML}_a^{r_b}$ of round $\widetilde{r}_b$ from LH_b to $MC_{b,a}$

A bit more detail...

II.1. Generate candidate key

if $|MC_{a,b}| >= N_a$
then $kh_a :=$
$H(s_a^{r_a} | last_{N_a}(MC_{a,b}))$
and $k_a :=$
$H(s_a^{r_a} | last_{N_a}(MC_{a,b}) | C)$

sufficient entropy collected

concatenate matches

if $|MC_{b,a}| >= N_b$
then $kh_b :=$
$H(s_b^{r_b} | last_{N_b}(MC_{b,a}))$
and $k_b :=$
$H(s_b^{r_b} | last_{N_b}(MC_{b,a}) | C)$

II.2. Exchange candidate keys

KEY $K_a :=< N_a, s_a^{r_a}, kh_a >$ →

← KEY $K_b :=< N_b, s_b^{r_b}, kh_b >$

optionally add list of round/candidate tuples

A bit more detail...

II.3. Search for candidate key

if $\exists \curlywedge$
$c_a \subseteq MC_{a,b}$
s.t. $H(\widetilde{s^r}_b | c_a) = \widetilde{kh}_b$
then $k'_b := H(\widetilde{s^r}_b | c_a | C)$

search because of multiple matches: $O(A^H)$

if $\exists \curlywedge$
$c_b \subseteq MC_{b,a}$
s.t. $H(\widetilde{s^r}_a | c_b) = \widetilde{kh}_a$
then $k'_a := H(\widetilde{s^r}_a | c_b | C)$

II.4. Acknowledge key

$\widetilde{\text{ACK } kh}_b$ →

← $\widetilde{\text{ACK } kh}_a$

II.5. Set key

if k_a is not set $k := k'_b$
if k'_b is not set $k := k_a$
if $\widetilde{kh}_a = \widetilde{kh}_b$
then $k := k_a$
else $k := k_a \oplus k'_b$

messages can overlap "in-flight"

if k_b is not set $k := k'_a$
if k'_a is not set $k := k_b$
if $\widetilde{kh}_b = \widetilde{kh}_a$
then $k := k_b$
$k := k_b \oplus k'_a$

And how to implement it?

From abstract channels to the real world

- Channels like ZigBee, WLAN are lossy
- UDP has comparable guarantees to such low-level broadcast channels

Effects of losing messages:

- CAND (candidate key parts) ⇒ can not be used as matches
- MATCH (match acknowledgments) ⇒ same as losing CAND
- KEY (candidate keys) ⇒ when no acknowledgement received, next KEY
- ACK (key acknowledgments) ⇒ same as losing KEY

Asynchronism

- general case: message received before local round processed ⇒ message history replay

What we missed on the first N tries

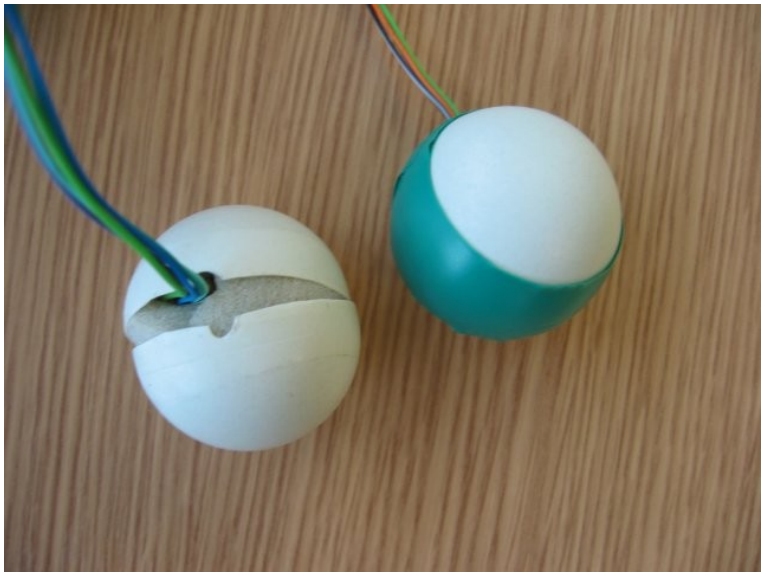
- Asynchronism (the “back to the future” problem)
- Checking for matches can't stop at the first match (the “early optimization” and the “the remote side may match the other way around” problems)
- Transmitting round/candidate tuples (the “but sometimes need to optimize” problem)
- Local synchronisation (the “oh, the remote talks at inconvenient times” and “now we're safe, but deadlocked” problems)
- Complete message buffers (the “how can we have a KEY message before its last CAND message?” problem)
- Exponential search complexity (the “don't use integers for computing factorials” problem)
- UDP sockets pecularities (the “under XYZ, UDP multicast doesn't loop back” and “oh, a host can have multiple interfaces?” problems)

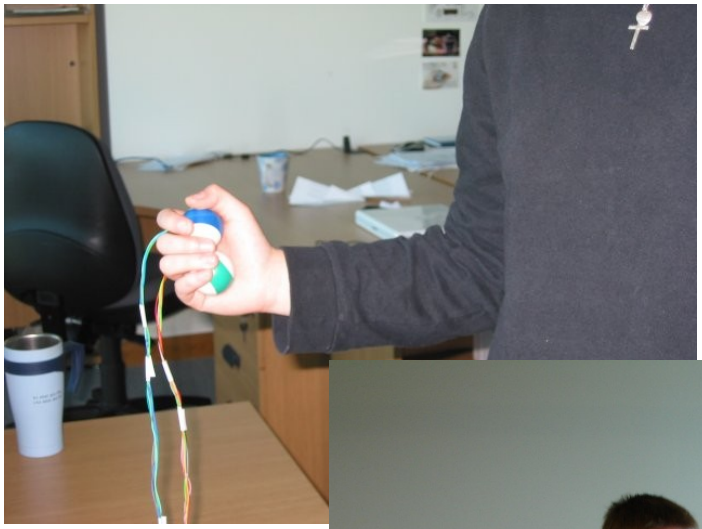
How we caught them

- Sanity checks
- Sanity checks (really!)
- Sanity checks (there's no such thing as “that variable **will** be set at this place”)
- Unit tests
- Write test cases before using a new class/method somewhere else (not quite as rigid as test-first, but highly valuable)
- Write test cases for cases you don't want to happen (“that will **never** be the case in practice” - right...)

Does it work?

- 2x 2D accelerometer per "device": ADXL202JE
- Sampled directly with the parallel port



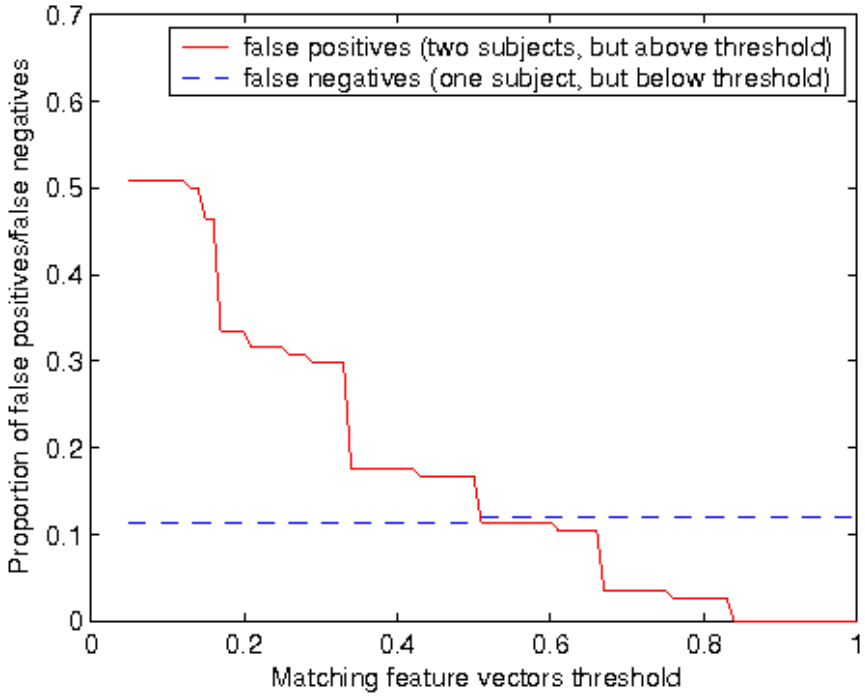


[MaGe 2007b] R. Mayrhofer, H. Gellersen: "Shake well before use: Authentication based on accelerometer data", Pervasive 2007

Does it work?

3 experiments:

- How do people shake?
- "Hacking" competition
- Live mode – does it work?



Results:

- Parameters for no false positives
- False negatives 11.96%
- 27/30 subjects reproducably successful within 10 tries or less
- Entropy of each feature vector estimated at ~7 bit

[MaGe 2007b] R. Mayrhofer, H. Gellersen: "Shake well before use: Authentication based on accelerometer data", Pervasive 2007

The bad

- Offline lookup table attacks possible when feature vectors have insufficient entropy
- CKP can not increase entropy of key material (related work suggests that entropy is at least retained)

The good

- Single, continuous phase
- Devices "tune into" each other's key streams
- Implicit authentication
- Opportunistic authentication
- Multi-device authentication
- Applicable to arbitrary feature vectors
- Open source (LGPL) reference implementation - "it's there"

The ugly

- Do MATCH messages reveal additional information?
- Can we increase the entropy by adding (more) random input (privacy amplification)?
- How best to counter attacks on asynchronism?

Summary: What have we done?

- Candidate Key Protocol interactively creates shared secret keys from common sensor data streams
- Multiple candidates for each time window reduce problems with noise
- Broadcasting hashes to find matches without revealing them
- Remote devices "tune into" candidate key stream
  - resource friendly
  - opportunistic
  - multi-device
- Implementation under LGPL at http://www.openuat.org

"plus valet in manibus avis unica quam dupla silvis"

Ca. 1200AD
A bird in the hand is worth two in the bush.

First International Workshop on Security for Spontaneous Interaction at Ubicomp 2007

Thank you for your attention!

Slides: http://www.mayrhofer.eu.org/presentations
Source code: http://www.openuat.org
Later questions: rene@mayrhofer.eu.org

OpenPGP key: 0xC3C24BDE
7FE4 0DB5 61EC C645 B2F1 C847 ABB4 8F0D C3C2 4BDE