The Fairy-Ring Dance: Password Authenticated Key Exchange in a Group

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Acknowledgment

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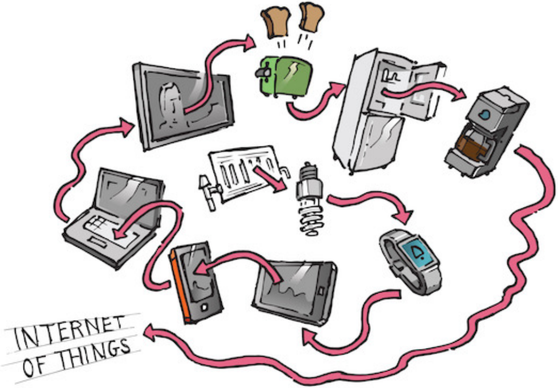
Internet of Things

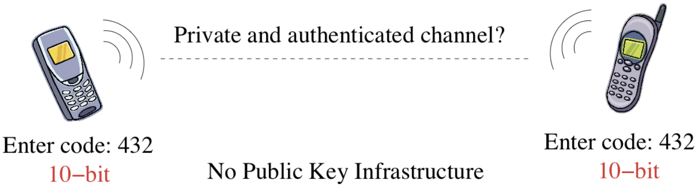


All communications via (insecure) Internet

Secure Group Communication

- The need for secure group communication
  - One group key is easier to manage than many pairwise keys
- Where to bootstrap the trust?
  - Not from PKI, as we want to avoid it
  - Instead, from a common (low-entropy) password
- In practice, one enters a short code to each device
  - No pre-installed certificates or secrets required

Password Authenticated Key Exchange



- Extensively studied since 1992
- Several solutions available: EKE, SPEKE, SRP-6, J-PAKE

Group PAKE

- A natural extension from two-party to multi-party
- However, not a trivial extension
  - Group PAKE is more difficult to design than two-party PAKE
  - Very few studies on Group PAKE so far
- However, IoT may prove a killer app for Group PAKE

Challenge in designing Group PAKE

- Security requirements have been well undrestood
  - Similar to two-party PAKE
- One practical challenge is to make it round-efficient
  - Computation improves rapidly over time (Moore's law)
  - Communication improves only modestly
  - The rounds always stay the same
- The overall latency is mainly determined by the slowest responder

Round efficiency

- Many Group PAKE protocols require $O(n)$ rounds
- Best round efficiency so far: constant 4 rounds (Abdalla et al, PKC'06)
- Here, we show how to achieve 2 rounds (theoretical best)

The topology of group communications

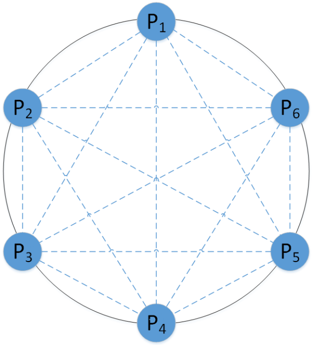
- Previous designs generally assume a circle
  - A participant only talks to two neighbors (left and right)
  - Essentially, following the same topology as Burmester-Desmedt (Eurocrypt'95)
- But we will use a different topology: fully-connected graph
  - No increase in the communication complexity
  - All data is broadcasted in the public

Fairy-Ring Dance

(Source: YouTube)

- A traditional Scottish dance
- Men and women form a circle, and dance in rotation
- Everyone dances with everyone else

A more technical view



- Run two processes in parallel
  - Pairwise PAKE sessions (inner dash lines)
  - One group session establishment (outer circle)

Two concrete instantiations

- SPEKE+
  - Use SPEKE for pairwise PAKE sessions
  - Use (modified) Burmester-Desmedt for group session
- J-PAKE+
  - Use J-PAKE for pairwise PAKE sessions
  - Use (modified) Burmester-Desmedt for group session

First Group PAKE scheme: SPEKE+

- Combining SPEKE and BD with optimal round-efficiency
- SPEKE
  - Proposed by Jablon in 1996
  - Standardized in IEEE P1363.2 and ISO/IEC 11770-4.
  - Used in commercial applications (Blackberry)
- BD
  - Proposed by Burmester and Desmedt in 1995
  - Almost universally used in group key exchange schemes
  - But it's unauthenticated

SPEKE protocol [Jablon'96]

	Alice		Bob
1.	$x \in_R Z_q$	$\xrightarrow{X = g^x}$	Verify $X \in [2, p-2]$
2.	Verify $Y \in [2, p-2]$	$\xleftarrow{Y = g^y}$	$y \in_R Z_q$
	$\kappa = H(Y^x) = H(g^{xy})$		$\kappa = H(X^y) = H(g^{xy})$
Explicit key confirmation (optional)			

- Use a safe prime $p = 2q + 1$
- Use a password-derived generator: $g = s^2$ (later changed to $g = H(s)^2$)

BD protocol [Burmester-Desmedt'95]

Round 1

Every participant P_i selects $y_i \in_R [0, q-1]$ and broadcasts g^{y_i}.

Everyone can compute $g^{z_i} = g^{y_{i+1}} / g^{y_{i-1}}$.

Round 2

Every participant P_i broadcasts $(g^{z_i})^{y_i}$.

Group session key:

$$K_i = (g^{y_{i-1}})^{n \cdot y_i} \cdot (g^{z_i y_i})^{n-1} \cdot (g^{z_{i+1} y_{i+1}})^{n-2} \cdots (g^{z_{i-2} y_{i-2}})$$
$$= g^{y_1 \cdot y_2 + y_2 \cdot y_3 + \cdots + y_n \cdot y_1}$$

SPEKE+ (Two rounds with key confirmation)

Round 1

Every participant P_i selects $x_i \in_R [1, q-1]$, $y_i \in_R [0, q-1]$ and broadcasts $g_s^{x_i}$, g^{y_i} together with ZKP for y_i.

Everyone can compute $g^{z_i} = g^{y_{i+1}} / g^{y_{i-1}}$.

Round 2

Every participant P_i broadcasts $(g^{z_i})^{y_i}$ and a ZKP for proving $\mathrm{Log}_{g^{z_i}} (g^{z_i})^{y_i} = \mathrm{Log}_g g^{z_i}$. Furthermore, P_i computes two pairwise keys with each of the rest participants: 1) $\kappa_{ij}^{\mathrm{MAC}} = H(g_s^{x_i x_j} \| \text{"MAC"})$; 2) $\kappa_{ij}^{\mathrm{KC}} = H(g_s^{x_i x_j} \| \text{"KC"})$. The 1st key is used to authenticate the group key while the 2nd key is used for key confirmation in pairwise PAKE sessions. (more details in paper)

$$K_i = (g^{y_{i-1}})^{n \cdot y_i} \cdot (g^{z_i y_i})^{n-1} \cdot (g^{z_{i+1} y_{i+1}})^{n-2} \cdots (g^{z_{i-2} y_{i-2}}) \\ = g^{y_1 \cdot y_2 + y_2 \cdot y_3 + \cdots + y_n \cdot y_1}$$

Second Group PAKE scheme: J-PAKE+

- J-PAKE [Hao, Ryan, 2008]
  - Included in open source libraries (OpenSSL, Bouncycastle, NSS)
  - Used in commercial applications (Firefox, Palemoon, Nest)
  - Accepted by ISO/IEC 11770-4 standard (in process)
- J-PAKE+ (our new contribution)
  - A group variant of J-PAKE

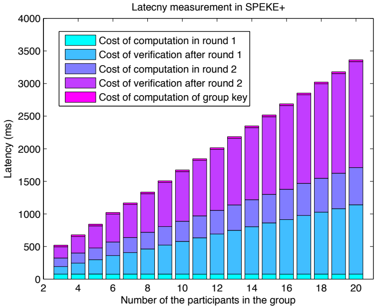
J-PAKE+

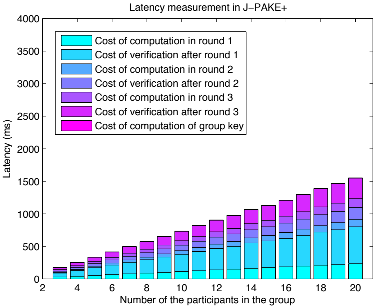
- Original two-party J-PAKE
  - Two rounds with implicit key confirmation
  - Three rounds with explicit key confirmation
- Multi-party J-PAKE+
  - Combining J-PAKE and BD with optimal round-efficiency
  - Three rounds with explicit key confirmation
  - Based on the same Fairy-Ring Dance construction
  - Protocol details omitted in this talk (see paper)

Implementation of SPEKE+ and J-PAKE+

- Implemented both protocols in pure Java
- Used only the standard BigInteger class for all the modular exponentiations
- Chose the 2048-bit group setting
- Source code available at: `https://github.com/FairyRing/SourceCode`

Comparing latency between SPEKE+ and J-PAKE+

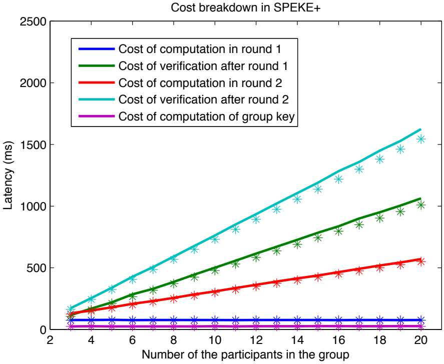




Tested on 2.93 GHz PC with 4 GB RAM running 64-bit Windows 7

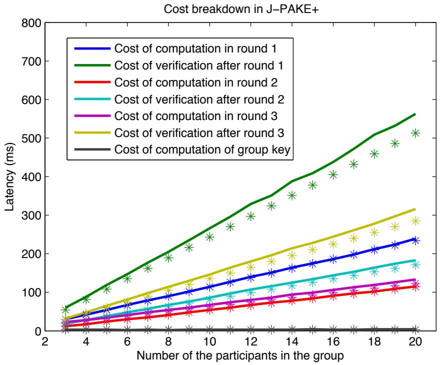
Breakdown of costs in SPEKE+

	Cost breakdown	Complexity	No of exponentiations
1	Computation in R1	$O(1)$	3
2	Verification after R1	$O(n)$	$(n-1)\times 2.215$
3	Computation in R2	$O(n)$	$3+(n-1)\times 1$
4	Verification after R2	$O(n)$	$(n-1)\times 3.25$
5	Compute group key	$O(1)$	1



Breakdown of costs in J-PAKE+

	Cost breakdown	Complexity	No of exponentiations
1	Computation in R1	$O(n)$	$2+(n-1)\times 4$
2	Verification after R1	$O(n)$	$(n-1)\times 9$
3	Computation in R2	$O(n)$	$(n-1)\times 2$
4	Verification after R2	$O(n)$	$(n-1)\times 4$
5	Computation in R3	$O(n)$	$5+(n-1)\times 2$
6	Verification after R3	$O(n)$	$(n-1)\times 5$
7	Compute group key	$O(1)$	1



Security properties of SPEKE+ and J-PAKE+

- Off-line dictionary attack resistance
  - Reducible to the underlying PAKE
- known-session security
  - Reducible to the underlying PAKE
- Forward secrecy
  - Reducible to the underlying PAKE
- On-line dictionary attack resistance
  - Reducible to the underlying PAKE
  - However, the number of guesses increases to $\alpha \times (n - \alpha)$ where α is the number of legitimate participants and n is the total number of participants

The Good and Bad about Fairy-Ring Dance

- The Good
  - Preserves the round efficiency in the optimal way
  - Allows us to achieve better round efficiency than previous works
  - Pushes the known best result to 2 rounds (theoretical best)
- The Bad
  - More than one password guesses in on-line attack: ideally, should be exactly one
  - $O(n)$ computation per participant: ideally, should be $O(1)$
- However, need to put the "Bad" into a practical perspective
  - Not any serious concern for a small-medium sized group
  - Overall, a worthwhile trade-off

Conclusion

- Research on two-party PAKE started from 1990s
  - Extensively studied in the past 20 years
  - Practical deployment of PAKE only takes off in recent years
- Research multi-party Group PAKE has been lagging far behind
  - Very few studies in this area
  - No Group PAKE has been used in any practical applications
  - However, the IoT may change the landscape
- We contribute two Group PAKEs
  - Both are are sufficiently efficient for practical use
  - Open source implementations available

Q & A

Thank you!

For more technical details, see
`https://eprint.iacr.org/2015/080.pdf`