Terrorist Fraud in Quantum Distance Bounding

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June 18th, 2020

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Outline

Distance Bounding

Use cases

- Contactless payments
- Remote “keyless” entry systems
- Building access

Solution

- measure round-trip time

Alternative solutions

- Signal strength
  - Wi-Fi positioning system (WPS)
- Faraday cage
- do nothing

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BlueSniper [Fle04]

Distance Bounding

Measure round-trip time in challenge-response protocol:

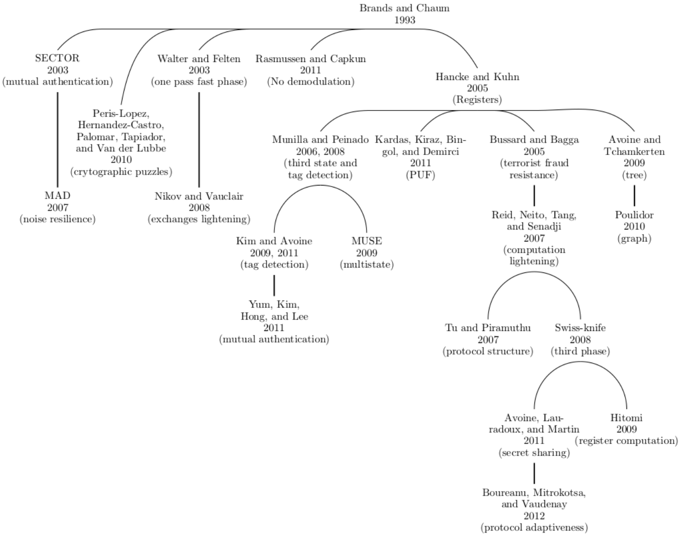
- speed of information is bound by $c \approx 300{,}000\text{km/s}$
- distance $\leq c \cdot$ round-trip-time

Problem: computers are slow

- typical smartcard clock 13.56MHz
- one clock cycle corresponds to 11 meter
- more overhead from analog-to-digital conversion and back

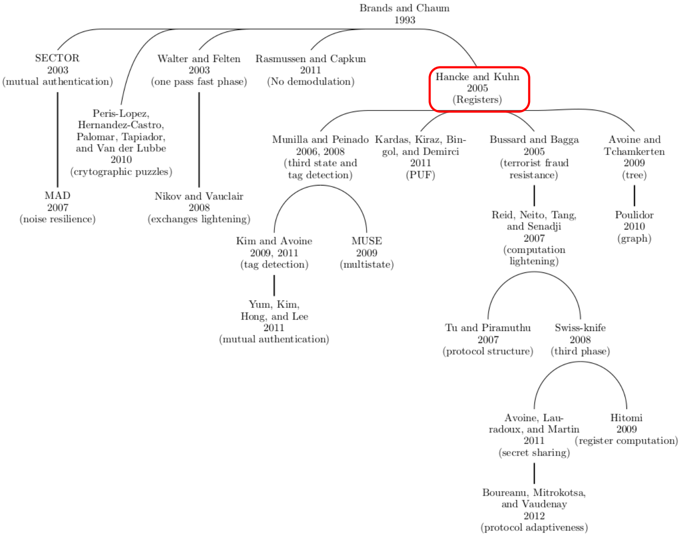
Solution: multiple phase protocol

- slow phase for crypto
- timed phase:
  - implement directly in hardware
  - only very simple operations



Distance bounding protocols, 2018 survey [Avo+18]

Distance Bounding



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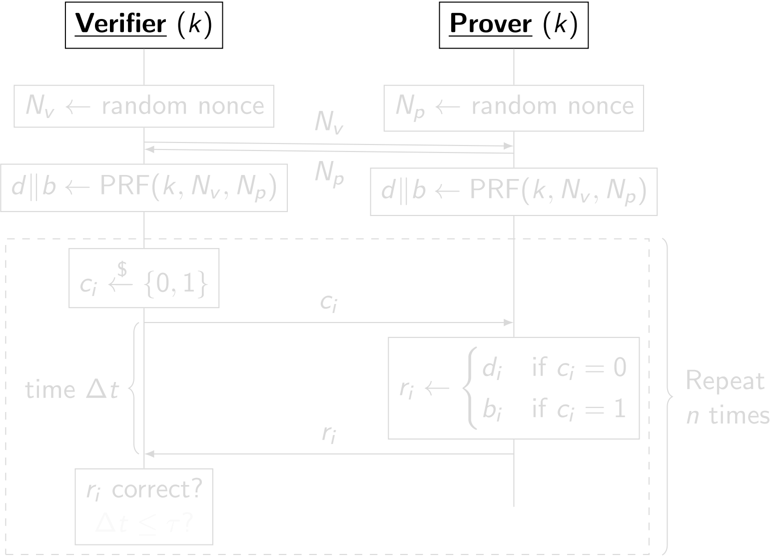
Hancke & Kuhn 2005 [HK05]



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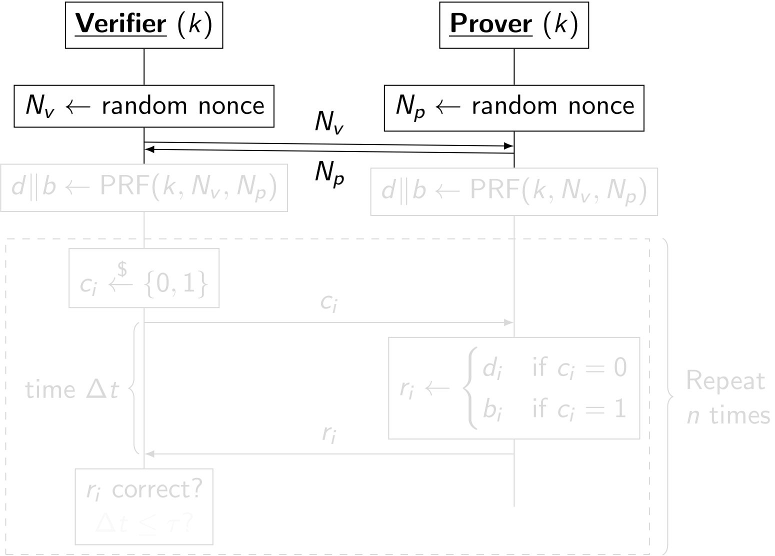

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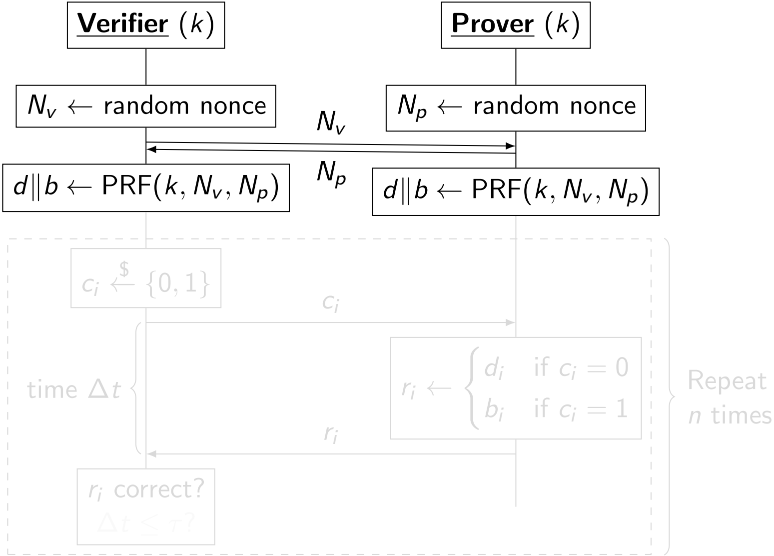

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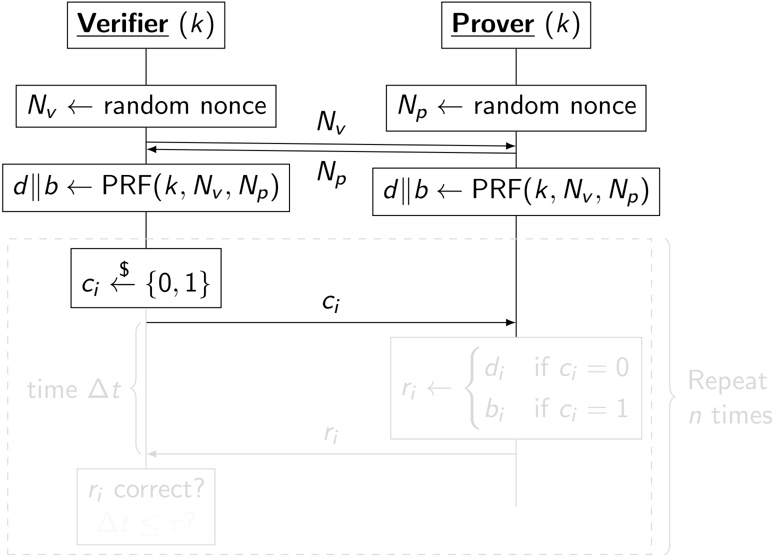

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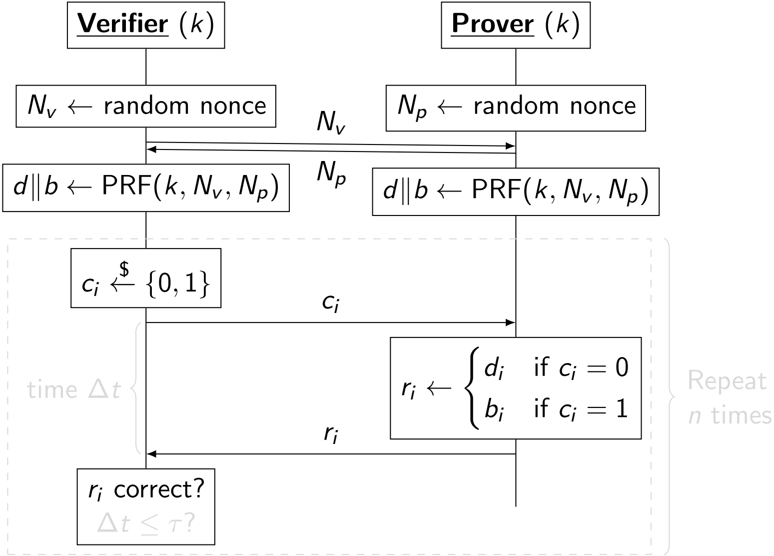

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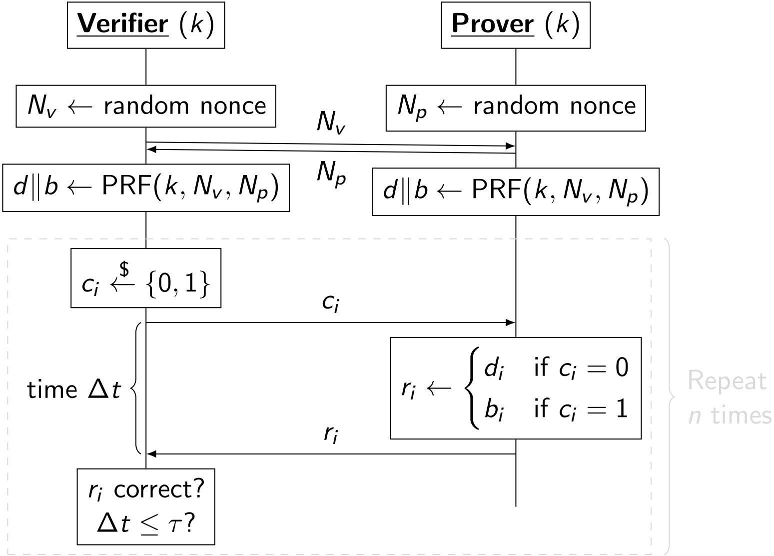

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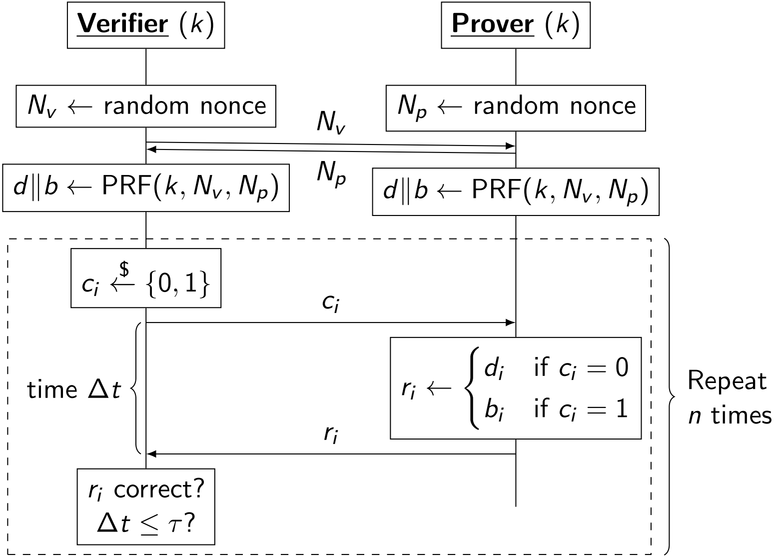
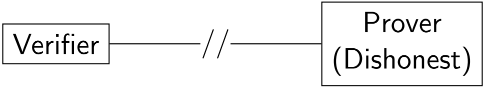
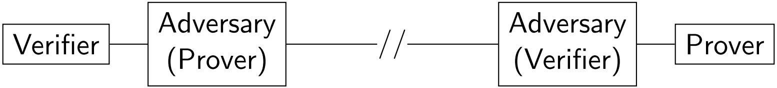


Distance Fraud



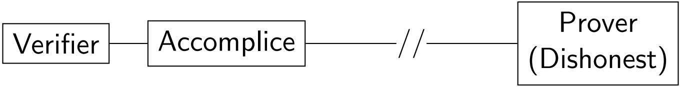
- Prover attempts to convince the verifier that they are nearby
- Countermeasure:
  - Randomize challenges c_i: preventing the prover from sending responses early

Mafia Fraud (relay attack)



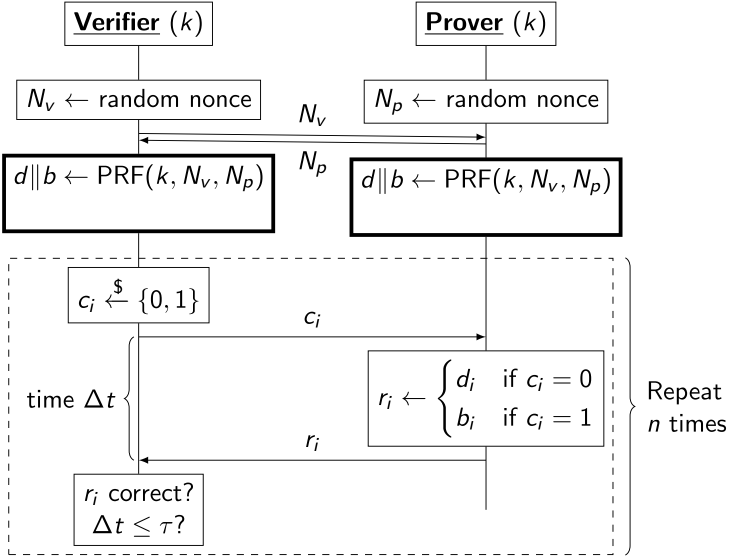
- Adversary attempts to convince the verifier that they are the prover
- Countermeasure:
  - Adversary cannot create correct responses without knowledge of secret key k
  - Relaying the challenges to the prover is too slow

Terrorist Fraud (assisted relay attack)



- Variation on Mafia fraud, but now the prover assists the accomplice
  - Trivial: Prover gives secret key k to the accomplice
- To exclude the trivial attack, assume the prover only wants to provide one-time access
- There is much debate about the usefulness and formalization of terrorist fraud
- Hancke-Kuhn does not resist terrorist fraud

Hancke-Kuhn



Verifier (k)
Prover (k)
$N_v \leftarrow$ random nonce
$N_p \leftarrow$ random nonce
N_v
N_p
$d \| b \leftarrow \mathrm{PRF}(k, N_v, N_p)$
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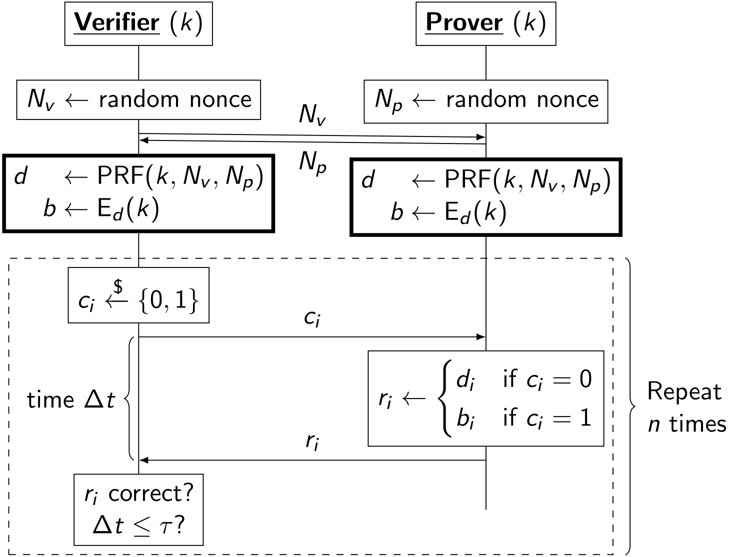
$c_i \xleftarrow{\$} \{0, 1\}$
c_i
time Δt
$r_i \leftarrow \begin{cases} d_i & \text{if } c_i = 0 \\ b_i & \text{if } c_i = 1 \end{cases}$
r_i
r_i correct?
$\Delta t \leq \tau$?
Repeat
n times

Hancke-Kuhn with terrorist fraud resistance*



Out of scope

- Noise
- Anonymity
- Distance Hijacking
- Position based cryptography

Notation:

- initial phase is identical: omitted from the slides
    - no information theoretic security: initial phase relies on a PRF

qubit: $|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle = \begin{pmatrix}\alpha\\ \beta\end{pmatrix}$

- (complex) amplitudes α, β

$x \leftarrow$ measure $|\psi\rangle$

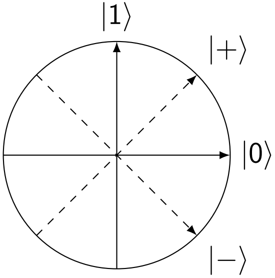
- $\Pr[x = 0] = |\alpha|^2$
- $\Pr[x = 1] = |\beta|^2 = 1 - |\alpha|^2$

Hadamard basis

- $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$
- $|-\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$

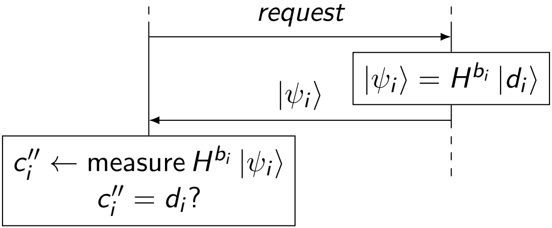
Hadamard gate H

- $H\,|0\rangle = |+\rangle$; $H\,|1\rangle = |-\rangle$
- $H\,|+\rangle = |0\rangle$; $H\,|-\rangle = |1\rangle$



Relay attacks detection protocol

RAD protocol by Jannati & Ardeshir-Larijani [JA16]



- no randomized challenge
- no timed phase
- security proof assumes that relaying requires measurement
- flaws observed by Abidin [Abi20]

Improved RAD, 2020

$$c_i \xleftarrow{\$} \{0,1\}$$

$$\xrightarrow{\quad c_i \quad}$$

$$|\psi_i\rangle = \begin{cases} H^{d_i}\,|0\rangle & \text{if } c_i = 0 \\ H^{b_i}\,|1\rangle & \text{if } c_i = 1 \end{cases}$$

$$\xleftarrow{\quad |\psi_i\rangle \quad}$$

$$c_i'' \leftarrow \text{measure} \begin{cases} H^{d_i}\,|\psi_i\rangle & \text{if } c_i = 0 \\ H^{b_i}\,|\psi_i\rangle & \text{if } c_i = 1 \end{cases}$$

$$c_i = c_i''?$$

- response is timed
- type of encryption E is unspecified (it matters!)

Extracting k from Improved RAD, 2020

If E is a one-time pad ($b = k \oplus d$):

- alter one rapid round in a session between honest participants
- extract a key bit $k_i = 1$
  - flip challenge c_i
  - forward response $|\psi_i\rangle$
  - observe if the verifier accepts
- if $k_i = 0$, then $d_i = b_i$:
  - verifier measures in "correct" basis
  - $c_i \neq c_i''$
  - verifier rejects
- if $k_i = 1$, then $d_i \neq b_i$:
  - verifier measures in non-orthogonal basis
  - verifier maybe accepts
- to extract $k_i = 0$, flip c_i and reply $H|\psi_i\rangle$
- repeat until all key bits are extracted ($3.5n$ sessions expected)

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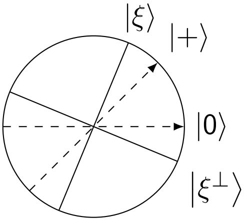
Terrorist fraud on Improved RAD, 2020

If E is a computational cipher (e.g. $b = \mathrm{AES}_d(k)$):

- extracting one bit of $d \oplus b$ is insufficient
- terrorist fraud is possible
  - prover completes the (slow) initial phase
  - prover sends $(H^{d_i}|0\rangle, H^{b_i}|1\rangle)$ to the accomplice
  - accomplice selects correct reply to c_i
- the accomplice cannot learn d_i (or b_i) with certainty

- best attempt: measure in basis $\{|\xi\rangle, |\xi^\perp\rangle\}$
- $|\xi\rangle = \cos\frac{3\pi}{8}|0\rangle + \sin\frac{3\pi}{8}|1\rangle$
- $|\xi^\perp\rangle = \cos\frac{-\pi}{8}|0\rangle + \sin\frac{-\pi}{8}|1\rangle$



- $|\langle\xi|+\rangle|^2 = |\langle\xi^\perp|0\rangle|^2 = (2+\sqrt{2})/4 \approx 0.85$

Terrorist fraud on Improved RAD, 2020 (cont.)

By the Holevo-Helstrom theorem, distinguishing equal probability pure states $|\psi\rangle, |\phi\rangle$ succeeds with probability at most

$$\frac{1}{2} + \frac{1}{2}\sqrt{1 - |\langle\phi|\psi\rangle|^2}$$

Since $\langle 0|+\rangle = 1/\sqrt{2}$, the optimum is indeed $(2 + \sqrt{2})/4$.
The accomplice learns k by getting all $2n$ bits of d and b.

- assuming the PRF and E are secure, these are independent
- so[1] the accomplice succeeds in extracting k with probability

$$\left(\frac{2 + \sqrt{2}}{4}\right)^{2n} \approx 0.73^n$$

[1] should be true, but I haven't proved it yet

$$c_i \xleftarrow{\$} \{0,1\}$$
$$|\phi_i\rangle = H^{d_i}\,|c_i\rangle$$

$$\xrightarrow{\quad |\phi_i\rangle \quad}$$

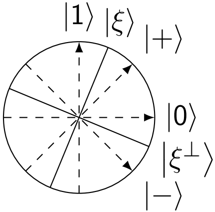
$$c_i' \leftarrow \text{measure } H^{d_i}\,|\phi_i\rangle$$
$$|\psi_i\rangle = H^{b_i}\,|c_i'\rangle$$

$$\xleftarrow{\quad |\psi_i\rangle \quad}$$

$$c_i'' \leftarrow \text{measure } H^{b_i}\,|\psi_i\rangle$$
$$c_i = c_i''?$$

If E is a one-time pad ($b = k \oplus d$), we can extract k:

- previous attack works (flip challenge qubit with XZ-gate), but we can do better
- interact only with the prover
  - send challenge $|\xi\rangle$ in every rapid round
  - measure response in $\{|\xi\rangle, |\xi\perp\rangle\}$ basis
  - associated guesses $k_i = 0$ or $k_i = 1$ (resp.)



Assume $d_i = 0$, then

$$\Pr[\text{guess } 0 \mid k_i = 0] = |\langle\xi|1\rangle|^2 |\langle 1|\xi\rangle|^2 + |\langle\xi|0\rangle|^2 |\langle 0|\xi\rangle|^2$$
$$= \left(\frac{2+\sqrt{2}}{4}\right)^2 + \left(\frac{2-\sqrt{2}}{4}\right)^2 = \frac{3}{4}$$

and

$$\Pr[\text{guess } 0 \mid k_i = 1] = |\langle \xi | + \rangle|^2 |\langle 0 | \xi \rangle|^2 + |\langle \xi | - \rangle|^2 |\langle 1 | \xi \rangle|^2$$
$$= 2\left(\frac{2+\sqrt{2}}{4}\right)^2 \left(\frac{2-\sqrt{2}}{4}\right)^2 = \frac{1}{4}$$

and similar when $d_i = 1$.

- repeat the experiment, with majority vote of guesses per bit
- error in guess for k_i becomes negligible by standard tail bounds on the binomial distribution

Terrorist fraud on Abidin, 2019

If E is a computational cipher (e.g. $b = \mathrm{AES}_d(k)$), terrorist fraud is possible:

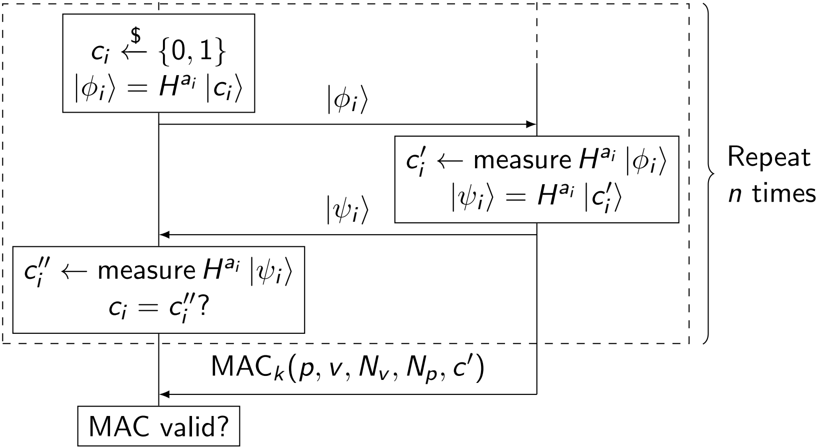
- $|\psi_i\rangle = H^{d_i \oplus b_i} |\phi_i\rangle$ (no measurement required)
- prover sends $d \oplus b$ to the accomplice

The challenge $|\phi_i\rangle = H^{d_i} |c_i\rangle$ does not leak d:

$$\frac{1}{2}\left(|0\rangle\langle 0| + |1\rangle\langle 1|\right) = \frac{1}{2}\left(|+\rangle\langle +| + |-\rangle\langle -|\right)$$

Abidin, Marin, Singelée, Preneel, 2017 [Abi+17]

For $b, d \in \{0,1\}^{n/2}$, let $a = d \| b$ in



If E is a one-time pad ($b = k \oplus d$), we can extract k:

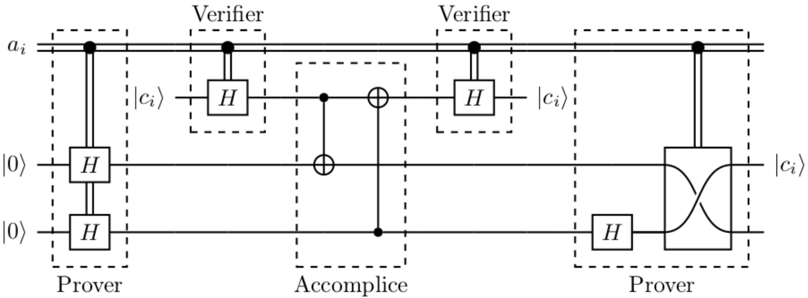
- interact only with the prover
- for every round: guess a_i' for encoding basis a_i
- send challenge $|\phi_i\rangle = H^{a_i'} |c_i\rangle$ (for some c_i)
- $c_i'' \leftarrow$ measure $H^{a_i'} |\psi_i\rangle$
  - if $a_i' = a_i$, then $|\psi_i\rangle = |\phi_i\rangle$ and $\Pr[c_i'' = c_i] = 1$.
  - if $a_i' \neq a_i$, then $|\psi_i\rangle \neq |\phi_i\rangle$ and $\Pr[c_i'' = c_i] = 1/2$.
- $\Pr[a_i' \neq a_i, c_i'' \neq c_i] = 1/4$
- if both d_i (round i) and b_i (round $i + n/2$) leak, then k_i leaks
  - probability $1/16$
  - can improve this by using partial information gained in previous attacks
- repeat the attack until all bits have leaked

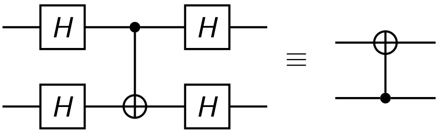
Terrorist fraud on AMSP

If E is a computational cipher (e.g. $b = \mathsf{AES}_d(k)$), terrorist fraud is possible:

- cloning the challenge would allow it
  - reflect one copy to the verifier
  - forward the other copy to the prover (to compute the MAC)
- no-cloning theorem prevents direct cloning
- the prover can assist the accomplice:
  - give $|00\rangle$ if $a_i = 0$
  - give $|{+}{+}\rangle$ if $a_i = 1$
- the prover can clone once using two CNOT gates

Terrorist fraud on AMSP (cont.)





Terrorist fraud on AMSP (cont.)

This does not leak a to the accomplice.

- challenge qubit does not help here either
- prover provided information reveals too little: best guess for a_i is correct with probability

$$\frac{1}{2} + \frac{1}{2}\sqrt{1 - |\langle 00|{+}{+}\rangle|^2} = \frac{2+\sqrt{3}}{4}$$

- so[2] accomplice guesses a correct with probability

$$\left(\frac{2+\sqrt{3}}{4}\right)^n \approx 0.93^n$$

[2] should be true but I don't have a proof yet

IT secure distance bounding

- most quantum cryptography aims to eliminate computational assumptions
- but these protocols require a one-way function
- one-time (classical) distance bounding protocols are already IT secure
  - $d \| b = k$
- combine with QKD to do multiple sessions
  - use the unused bits for authenticating a QKD session
- is that really quantum distance bounding?

Thank you

References

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