Mind your nonces: cryptanalysis of a privacy-preserving distance bounding protocol

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Outline

- Motivation
- Distance Bounding Protocols
- The Rasmussen - Čapkun (RČ) protocol
- Attack against the RČ protocol

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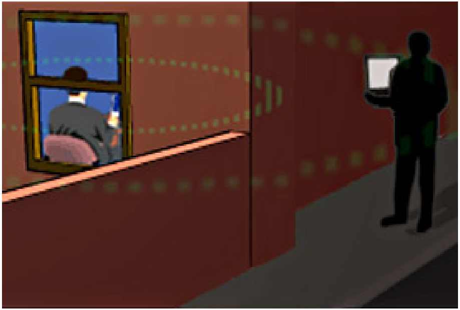
Motivation

Guarantees about the geographical location of a communicating device.

Secure Location Information

- Necessary in battlefield ad hoc networks
- Access Control Systems
- Satellite DTV conditional access systems
- Prevent location spoofing
- ...



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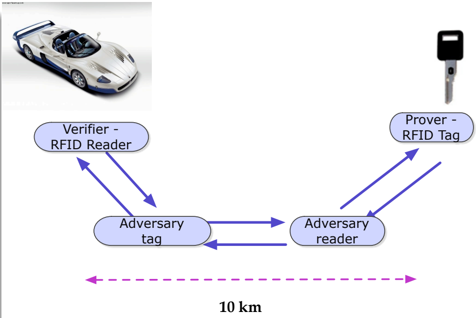
Relay attacks

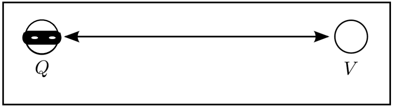
Relay attack

- Communication **Range**:
  a few **cm** or **dm** or even meters for RFID tags.
- Signal amplification⇒ increase this distance.
- Man-in-the-middle attack.
- The attacker relays messages from an authentic tag to a legitimate reader.



Relay Attacks

a) **Distance Fraud**
The attack is executed by a malicious prover Q. The goal is to shorten the distance measured by the verifier V.



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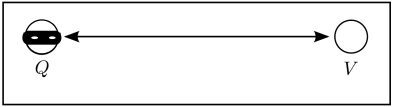
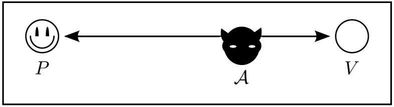


b) **Mafia Fraud**

The attack is executed by an external attacker A. The goal is to shorten the distance between an honest prover P and a verifier V.



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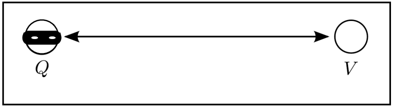

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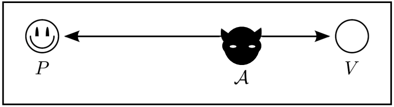
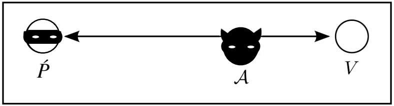


c) **Terrorist Fraud**

The attack is executed by a malicious prover A, colluding with a legitimate but dishonest prover P'. The goal is for P' to shorten his distance to the verifier V.



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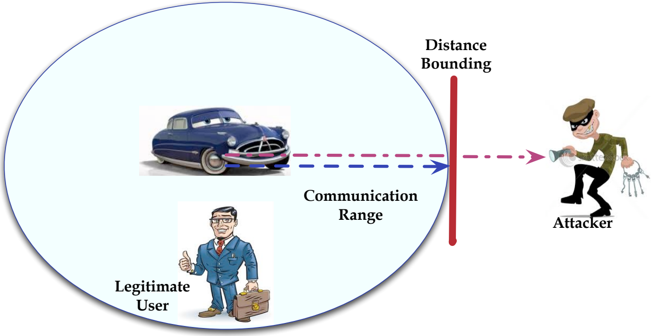
Distance Bounding Protocols

Countermeasure against relay attacks

- **Distance bounding** protocols: challenge-response authentication protocols.
- Enable a verifier (V) device to establish an upper bound on the physical distance to an untrusted prover device (P).
- Usually based on the response time of the prover (P) to estimate the distance.

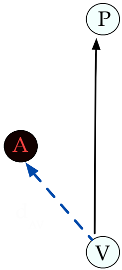


Distance Bounding Protocols

Prover P		**Verifier** V
shared key K		shared key K
	Initialization phase	
select a random N_P	$\xrightarrow{\text{commit}(N_P)}$	
	Rapid bit exchange	
		$c_1, \ldots, c_j \xleftarrow{\$} \{0,1\}$
	$\xleftarrow{c_1}$	
$r_1 \leftarrow f_{1,K}(c_1)$	$\xrightarrow{r_1}$	
$\ldots$	$\ldots$	$\ldots$
	$\xleftarrow{c_j}$	
$r_j \leftarrow f_{j,K}(c_j)$	$\xrightarrow{r_j}$	
		verify responses

Information Leakage in DB Protocols

Information leaks though the measurement of messages' arrival times.



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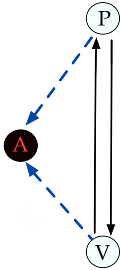

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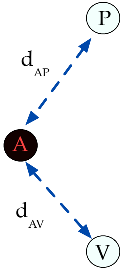

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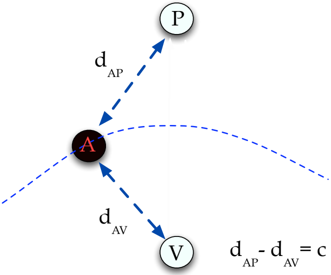

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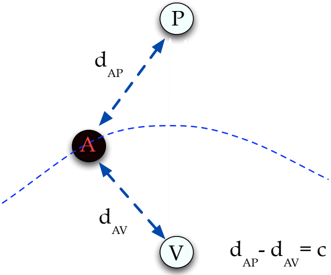

- Rasmussen & Čapkun have noted that DB protocols leak information about the distance and location of the *prover* and the *verifier*
- They proposed a *privacy - preserving* DB protocol.

The Rasmussen - Čapkun protocol

- P and V communicate over an insecure channel.
- When the protocol succeeds V is able to calculate an upper bound on the physical distance to P.
- Privacy preservation by hiding the RBE within a longer **uninterrupted stream** of bits.

The Rasmussen - Čapkun protocol

Notation

P and V share the knowledge of :

- A k-bit encryption key K_1.
- A k-bit authentication key K_2.
- A symmetric encryption scheme (Enc, Dec).
- A symmetric authentication scheme ($Sign$, $Verif$) i.e. a MAC.
- A pseudorandom generator connected to a source of physical entropy.
- A timestamp counter
- The bit length of N_P and N_V: n.
- The bit length of the *hidden marker* M: m

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The Rasmussen - Čapkun protocol

Prover P		**Verifier** V
shared keys K_1, K_2		shared keys K_1, K_2
	Initialization phase	
$N_P \xleftarrow{\$} \{0,1\}^n$ $c_1 \leftarrow \mathsf{Enc}_{K_1}(N_P)$ $t_1 \leftarrow \mathsf{Sign}_{K_2}(N_P)$	$\xrightarrow{c_1 \,\Vert\, t_1}$	$c_1' \,\Vert\, t_1'$
		$N_P' \leftarrow \mathsf{Dec}_{K_1}(c_1')$ if $\mathsf{Verif}_{K_2}(N_P', t_1') = \mathsf{error}$ then return error $M \xleftarrow{\$} \{0,1\}^m$
$c_2' \,\Vert\, t_2'$	$\xleftarrow{c_2 \,\Vert\, t_2}$	$c_2 \leftarrow \mathsf{Enc}_{K_1}(M \Vert N_P')$ $t_2 \leftarrow \mathsf{Sign}_{K_2}(M \Vert N_P')$
$M' \Vert N_P'' \leftarrow \mathsf{Dec}_{K_1}(c_2')$ if $N_P'' \neq N_P$ or $\mathsf{Verif}_{K_2}(M' \Vert N_P'', t_2') = \mathsf{error}$ then return error		$N_V \xleftarrow{\$} \{0,1\}^n$

The Rasmussen - Čapkun protocol

Prover P		**Verifier** V
shared keys K_1, K_2		shared keys K_1, K_2
	Distance bounding phase	
monitor traffic for detecting M	$\xleftarrow{\mathrm{Rand}_V()}$	bit-stream without M as a substring
	$\xrightarrow{\mathrm{Rand}_V() \oplus \mathrm{Rand}_P()}$	
	$\xleftarrow{M \parallel N_V}$	
when M is detected		
	$\xrightarrow{M \oplus \mathrm{Rand}_P() \parallel N_V \oplus N_P}$	
	$\xleftarrow{\mathrm{Rand}_V()}$	
	$\xrightarrow{\mathrm{Rand}_V() \oplus \mathrm{Rand}_P()}$	
stop after a random delay		stop after a random delay

The Rasmussen - Čapkun protocol

- During the *RBE* the bit streams between V and P are transmitted continuously on two different communication channels.
- By the **end of the** *RBE*
  V counts the **# of bits** received between:
  - the time he transmitted the first bit of N_V and
  - the time he received the first bit of $N_V \oplus N_P$.
- Given the bit rate and the processing delay,
  V can calculate the round trip time
  $\Rightarrow$ an **upper bound** on the distance to P.

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Attack against the RČ protocol

- A **passive** attack that recovers N_P, N_V and M for two sessions of the RČ protocol.
- An attacker is able to deduce information on the relative distance of P and V during each of those sessions.
- The distance between P and V does **not** need to be the same at each session.
- **How?** $\Rightarrow$ with repeated occurrences of the same N_P in two distinct sessions we can recover the ephemeral secrets of those sessions.

Attack against the RČ protocol

The attacker observes many sessions between P and V and:

Step 1: For each session observed:

- Record the two data streams exchanged after the c_2 is sent.
- Store the c_1's in a dynamically sorted table.
- When a c_1 value is repeated twice:
  - stop recording sessions,
  - delete the sessions where the repetitions do not occur.

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Attack against the RČ protocol

Step 2: For each of the two sessions with the same N_P, do:

- divide the V-to-P stream into n-bit windows VP_0, VP_1, ...
- divide the P-to-V stream into n-bit windows PV_0, PV_1, ...
- construct and sort a table containing all $VP_i \oplus PV_j$ values where $0 < i < j$.

Create two tables T_1 and T_2 one for each session using the same N_P.

Each table will contain an element equal to N_P.

Indeed the XOR between VP_i's and PV_i's will cancel the value of each N_V.

$(N_V \oplus (N_V \oplus N_P) = N_P)$.

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Attack against the RČ protocol

Step 3: Search for a collision between an element of T_1 and an element of T_2. If a unique collision is found then the value is N_P.

Step 4: Given $N_P \Rightarrow$ identify M and N_V in the bit-streams of each session.

Count the number of bits between the reception of N_V from the V and the reception of P's response

$\Rightarrow$ to **deduce** information on the relative **positions** of P and V.

Complexity analysis

- $\ell \rightarrow$ the least number of bits sent by either P or V during the distance bounding phase.

Memory required before detecting a collision

- N_P is n-bit long
- N_P will be repeated after approximately $2^{n/2}$

$\Rightarrow$ One needs to record $2 \cdot \ell \cdot 2^{n/2}$

Memory to store the tables

- $W = \ell - n + 1$, distinct windows of n-bits in the V-to-P stream.
- i-th window is XORed with $W - i - 1$, n-bit windows of the P-to-V stream. Thus, in total there are:

$$N = \sum_{i=1}^{W} (W - 1 - i) = \frac{W^2 - 3W}{2}$$

entries in each table.

Efficiency for typical parameters

- Communication channel of bit rate $1 Gbps$.
- Hidden marker M with length $m = 160$ bits.
- Distance bounding phase lasts 500 milliseconds.

(n, ℓ)	sessions monitored	memory required	tables size (N)	sorting time	number of collisions
$(32, 2^{10})$	2^{16}	2^{27}	2^{19}	2^{11}	2^{6}
$(32, 2^{20})$	2^{16}	2^{37}	2^{39}	2^{21}	2^{45}
$(64, 2^{10})$	2^{32}	2^{43}	2^{19}	2^{10}	1
$(64, 2^{20})$	2^{32}	2^{53}	2^{39}	2^{21}	2^{14}
$(64, 2^{30})$	2^{32}	2^{63}	2^{59}	2^{31}	2^{53}
$(128, 2^{10})$	2^{64}	2^{75}	2^{19}	2^{11}	1
$(128, 2^{20})$	2^{64}	2^{85}	2^{39}	2^{21}	1
$(128, 2^{30})$	2^{64}	2^{95}	2^{59}	2^{31}	1

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Strengthening the RČ protocol

- Probabilistic encryption: this way repetitions of N_P cannot be detected.
- Better nonces: unique N_P nonces should be used
  for example by using Bloom filters (to save memory)
- Encrypt-then-sign: instead of encrypt and sign
- Distinct keys: for authentication and encryption

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Conclusions

- Security analysis of the Rasmussen - Čapkun (RČ) protocol.
- Presented an attack that exploits nonce collisions.
- Proposed modifications of the protocol to thwart the attack.

Thank you for your attention!