Security Analysis of Distance Bounding Protocols

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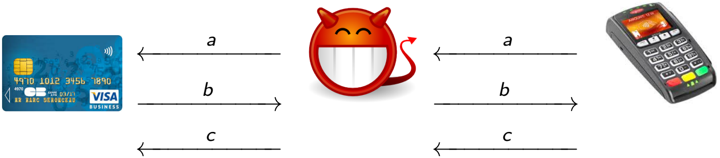
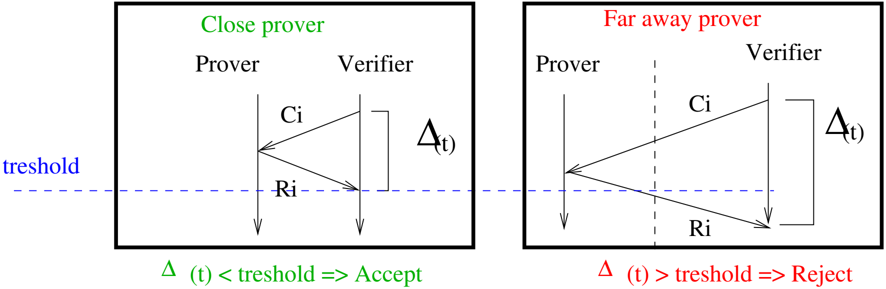
Context

Relay Attacks



Relay Attacks on Passive Keyless Entry and Start Systems in Modern Cars,
A. Francillon, 2011

Counter measure : RTT check



Brands & Chaum : Protocol

Verifier V public key : y		Prover P secret key : x
	Initialisation phase	
	$\xleftarrow{\text{commit(m)}}$	$m \xleftarrow{\$} \{0,1\}^n$
	Distance Bounding phase for $i = 1$ to n	
Pick $c_i \in \{0,1\}$		
Start clock	$\xrightarrow{c_i}$	
Stop clock	$\xleftarrow{r_i}$	$r_i := m_i \oplus c_i$
Check timers Δt_i		
	Verification phase	
Check responses	$\xleftarrow{\text{open commitment}}$	
Check signature	$\xleftarrow{\text{Sign}_x(S)}$	$S := c_1 \| r_1 \| ... \| c_n \| r_n$
	$\xrightarrow{\text{Out}_V}$	

Distance Bounding Protocol

Verifier V shared key : x		Prover P shared key : x
	Initialisation phase	
	$\xrightarrow{Messages_V}$	
	$\xleftarrow{Messages_P}$	
	$a = f_x(Messages_V, Messages_P)$	
	Distance Bounding phase	
	for $i = 1$ to n	
Start clock	$\xrightarrow{c_i}$	
Stop clock	$\xleftarrow{r_i}$	$r_i = F(c_i, a_i, x_i)$
	Verification phase	
Check Δt_i, r_i and S	$\xleftarrow{S}$	$S = sign_x(transcript)$

Honest Prover

Mafia Fraud (MF) : an adversary $\mathscr{A}$ tries to prove that a prover P is close to a verifier V.

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Impersonation Fraud (IF) : an adversary tries to impersonate the prover to the verifier.

$$\mathscr{A} \leftrightarrow V$$

Dishonest Prover

Distance Fraud : a far-away prover P^* tries to prove that he is close to a verifier V.

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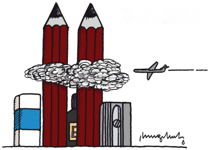

Terrorist Fraud (TF) : a far-away prover P^* helps an adversary $\mathscr{A}$ to prove that P^* is close to a verifier V without giving $\mathscr{A}$ another advantage.

$$P^* \leftrightarrow \mathscr{A} \leftrightarrow V$$

Motivations

- No exhaustive list of DB protocols.
- No compared or classified.
- No relationship between threat models.

Plan

1. Relations between Model of Threat
2. Attack and defence strategies
3. Conclusion and Perspective

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The BMV Model(2013)

Distance Fraud (DF) :

$$P^*(x) \leftrightarrow (P_1(x'), \dots, P'_m(x') \leftrightarrow V_1(y'), \dots, V_m(y') \leftrightarrow) V(y; r_V)$$

Man-In-the-Middle (MiM) :

$$P_1(x), ..., P_m(x) \leftrightarrow \mathscr{A}_1 \leftrightarrow V_1(y), ..., V_z(y)$$
$$P_{m+1}(x), ..., P_l(x) \leftrightarrow \mathscr{A}_2(View_{\mathscr{A}_1}) \leftrightarrow V(y)$$

Collusion Fraud (CF) :

$$P^*(x) \leftrightarrow \mathscr{A}^{\mathrm{CF}} \leftrightarrow V_0(y)$$

- $X \rightarrow Y$ denotes that if the property X is satisfied then Y is also satisfied, an attack on the property Y implies an attack on the property X.

DF **MiM**

DH **CF**

TF MF IF

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- $X \rightarrow Y$ denotes that if the property X is satisfied then Y is also satisfied, an attack on the property Y implies an attack on the property X.
- $X \dashrightarrow Y$ denotes that an attack on the property Y without sending the secret x implies an attack on the property X.

TF $\dashrightarrow$ DF

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Theorem (TF $\dashrightarrow$ DF)

If a protocol is not α-resistant to DF, then there exists an attack of kind TF which succeed with probability at least α.

Proof : If $P^* \longleftrightarrow V$ succeeds, then $P^* \longleftrightarrow \mathscr{A}^{\text{TF}} \longleftrightarrow V$ succeeds with the same probability, if P^* does not transmit his secret and $\mathscr{A}^{\text{TF}}$ simply relays messages. □

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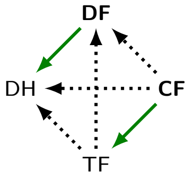

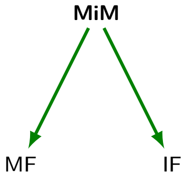

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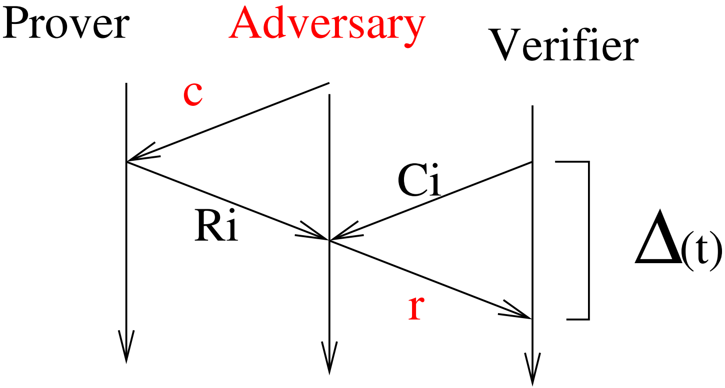
Attack Strategies : Mafia Fraud

- Pre ask strategy

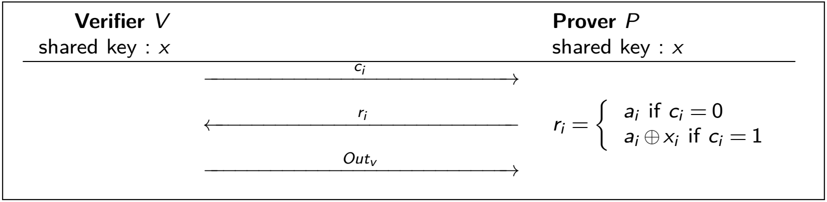


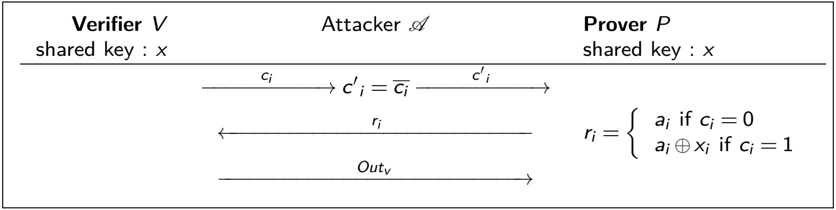
If $c == c_i$*,* $\mathscr{A}$ *knows* r_i*. Else, he has to guess.* $\mathscr{A}$ *wins if he gives a good* r_i *at all rounds*

$\left(\frac{1}{2}\cdot 1+\frac{1}{2}\cdot\frac{1}{2}\right)^n=\left(\frac{3}{4}\right)^n$. Defence : Signature of the transcript

Attack Strategies : Impersonation Fraud

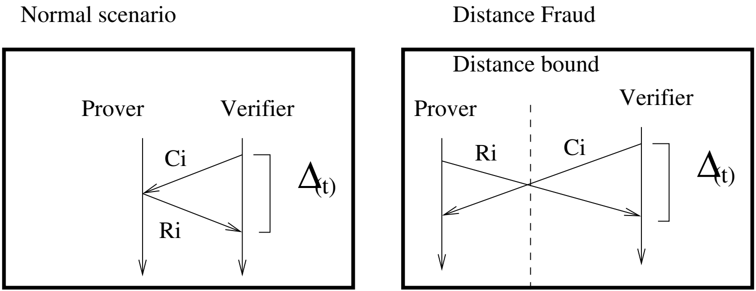
- Key recovery





If $Out_v = 1$, $a_i == a_i \oplus x_i$, so $x_i = 0$. Else, $x_i = 1$. After n executions, $\mathscr{A}$ recovers the whole key ! Defense : The responses can not just be a xor between the key and a one time pad.

Attack Strategies : Distance fraud



Two possible responses : if $c_i = 0$, $r_i = a_i$ and if $c_i = 1$, $r_i = b_i$.
$\left(\frac{1}{2} \cdot 1 + \frac{1}{2} \cdot \frac{1}{2}\right)^n = \left(\frac{3}{4}\right)^n$.

- Defence : The 2 possible responses should be complementary

Attack Strategies : Distance fraud : Example

Let g be a PRF and f a PRF constructed as follows :

$$f_x(M_V, M_P) = \begin{cases} a||a \text{ if } M_P = z \\ g_x(M_V, M_P) \text{ otherwise} \end{cases} \quad f_x \text{ is a PRF.}$$

Verifier V		**Prover** P
shared key : x		shared key : x
	Initialisation phase	
	$\xrightarrow{M_V}$	
	$\xleftarrow{M_P}$	$M_P = z$
	$a\|\|a = f_x(M_V, M_P)$	
	Distance Bounding phase	
	for $i = 1$ to n	
Start clock		
Stop clock	$\xleftarrow{r_i}$	$r_i = \begin{cases} a_i \text{ if } c_i = 0 \\ a_i \text{ if } c_i = 1 \end{cases}$
	$\xrightarrow{c_i}$	
Check Δt_i, r_i		

Defense : The PRF output should not be split in several parts.

Attack Strategies : Terrorist fraud

Verifier V shared key : x	Accomplice $\mathscr{A}$	**Prover** P shared key : x
	Initialisation phase	
	$\xrightarrow{NV}$	
	$\xleftarrow{NP}$	
$a = f_x(NP, NV)$		$a = f_x(NV, NP)$
Stop clock	$\xleftarrow{a}$	
	Distance Bounding phase for $i = 1$ to n	
Start clock	$\xrightarrow{c_i}$	
Stop clock	$\xleftarrow{r_i}$ $r_i = a_i \oplus c_i$	
	Verification phase	
Check Δt_i, r_i and S	$\xleftarrow{S}$	$S = sign_x(transcript)$

P can give a to $\mathscr{A}$ and allow a terrorist fraud with success probability 1, since a does not link any information about the secret key. Defense : Making the responses related to the key

Improvements of Attacks : TF, IF, DH

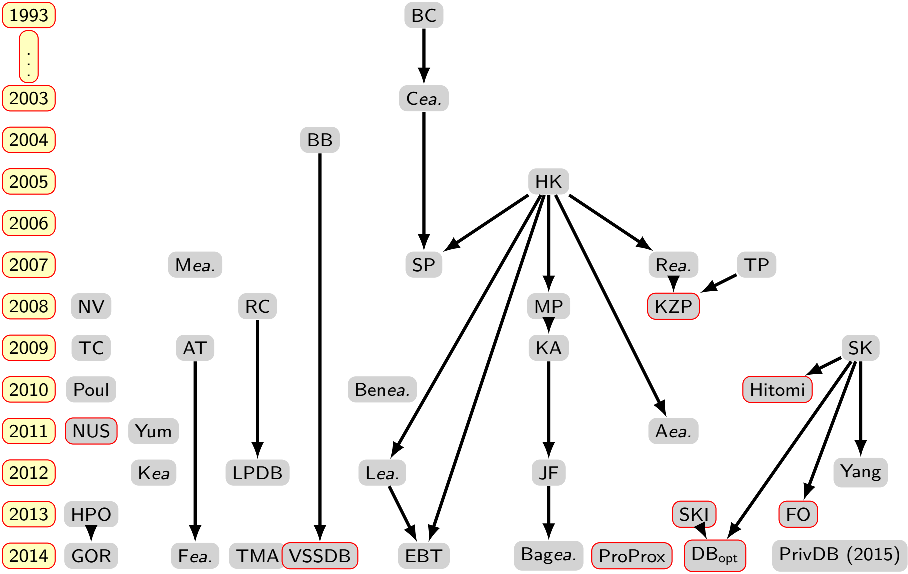
IF : Threat model few considered.
Exhaustive research on the key.
$\left(\frac{1}{2}\right)^s$, where s is the size of the key.

DH : Threat model few considered.
P^* hopes that P responds correctly to V.
$\left(\frac{1}{2}\right)^n$, where n is the number of round in the DB phase.

TF : P^* gives responses to $\mathscr{A}$. So, TF mainly filled with 1.

Survey

- 42 protocols from 1993 to 2015.



Survey

- 82 improvements = 28 DH + 10 DF + 0 MF + 30 IF + 1 MiM + 13 TF/CF.

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- 9 survivors : no attacks with probability of success at 1.

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Protocols	Success Probability						
	DH	**DF**	MF	IF	**MiM**	TF	**CF**
KZP (2008)	$(\frac{1}{2})^n$	$(\frac{3}{4})^n$ [8]	$(\frac{1}{2})^n$ [8]	$(\frac{1}{2})^s$	$(\frac{1}{2})^n$ [8]	$(\frac{3}{4})^v$ [8]	$(\frac{3}{4})^v$ [8]
Hitomi (2010)	$(\frac{1}{2})^n$ [5]	$(\frac{3}{4})^n$	$(\frac{1}{2})^n$ [9]	$(\frac{1}{2})^n$	$(\frac{1}{2})^n$ [9]	$(\frac{3}{4})^v$ [9]	$(\frac{3}{4})^v$ [9]
NUS (2011)	$(\frac{1}{2})^n$	$(\frac{3}{4})^n$ [1]	$(\frac{1}{2})^n$ [7]	$(\frac{1}{2})^n$ [7]	$(\frac{1}{2})^n$ [7]	$(\frac{3}{4})^v$	$(\frac{3}{4})^v$
SKI_{pro} (2013)	$(\frac{1}{2})^n$	$(\frac{3}{4})^n$ [2]	$(\frac{2}{3})^n$ [2]	$(\frac{1}{2})^s$	$(\frac{2}{3})^n$ [2]	$(\frac{5}{6})^v$ [3]	$(\frac{5}{6})^v$ [3]
Fischlin & Onete (2013)	$(\frac{1}{2})^n$	$(\frac{3}{4})^n$ [10]	$(\frac{3}{4})^n$ [10]	$(\frac{1}{2})^{2s}$	$(\frac{3}{4})^n$ [10]	$(\frac{3}{4})^v$ [10]	$(\frac{3}{4})^v$ [10]
DB1 (2014)	$(\frac{1}{t})^n$	$(\frac{1}{t})^n$ [4]	$(\frac{1}{t})^n$ [4]	$(\frac{1}{2})^s$	$(\frac{1}{t})^n$ [4]	$(\frac{t-1}{t})^v$ [4]	$(\frac{t-1}{t})^v$ [4]
DB2 (2014)	$(\frac{1}{2})^n$	$\left(\frac{1}{\sqrt{2}}\right)^n$ [4]	$(\frac{1}{2})^n$ [4]	$(\frac{1}{2})^s$	$(\frac{1}{2})^n$ [4]	$\left(\frac{1}{\sqrt{2}}\right)^v$ [4]	$\left(\frac{1}{\sqrt{2}}\right)^v$ [4]
ProProx (2014)	$(\frac{1}{2})^{n \cdot s}$	$\left(\frac{1}{\sqrt{2}}\right)^{ns}$ [11]	$(\frac{1}{2})^{ns}$ [11]	$(\frac{1}{2})^s$ [11]	$(\frac{1}{2})^{ns}$ [11]	$\left(\frac{1}{\sqrt{2}}\right)^{ns}$ [11]	$\left(\frac{1}{\sqrt{2}}\right)^{ns}$ [11]
VSSDB (2014)	$(\frac{1}{2})^n$	$(\frac{3}{4})^n$ [6]	$(\frac{1}{2})^n$ [6]	$(\frac{1}{2})^{2s}$ [6]	$(\frac{1}{2})^n$ [6]	$(\frac{3}{4})^v$ [6]	$(\frac{3}{4})^v$ [6]

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Conclusion and Perspective

- The **relationship** between threats models.
- Identify more easily the properties of a DB protocols.
- Compilation and classification of **42 protocols**.
- **Graph of dependency**.
- **82 improvements** of attacks.
- **9 still secure** protocols.
- **Tool box :** strategies of attack/defense.

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Futur works :

- Formal verification.
- Best protocol design.

Thanks for your attention !

Questions ?

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