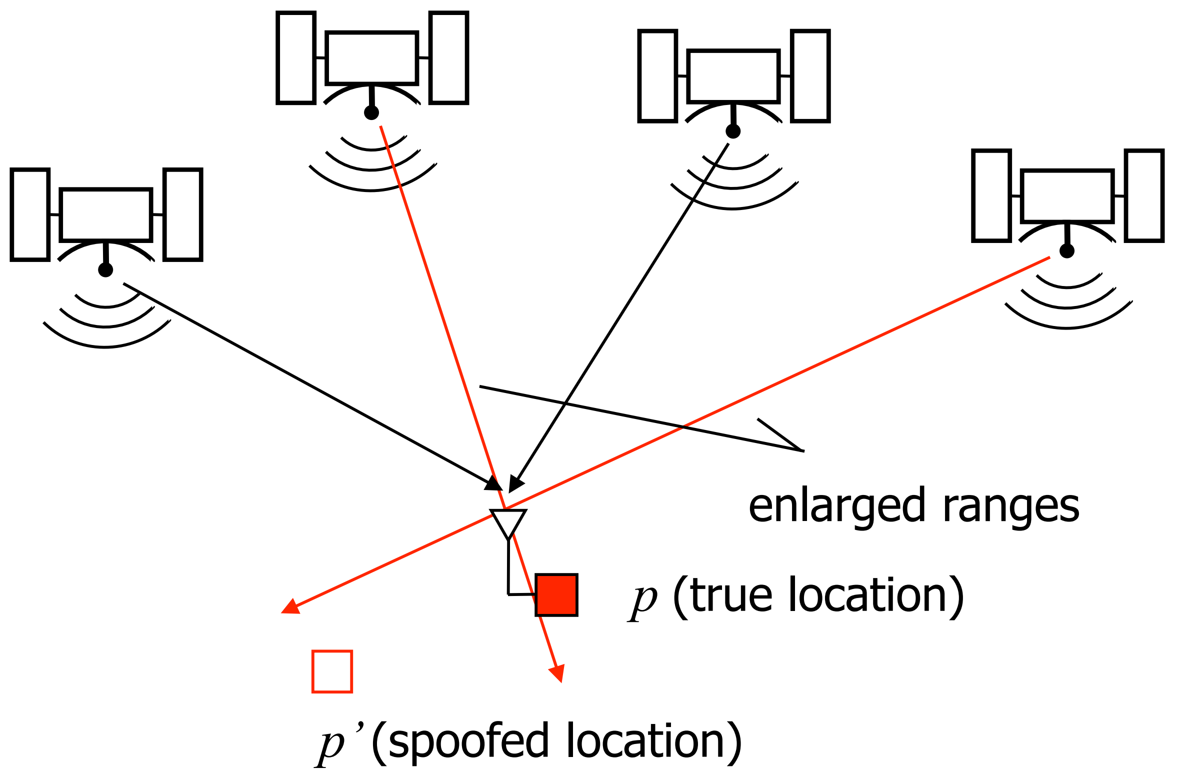
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

# Security of Wireless Networks


Srdjan Čapkun
*Department of Computer Science*
*ETH Zurich*

# GPS Spoofing can be Prevented in a number of Scenarios but …

*Broadcast systems like GPS cannot be **fully** secured*
***(ASSUMING DY ATTACKER) !!!***



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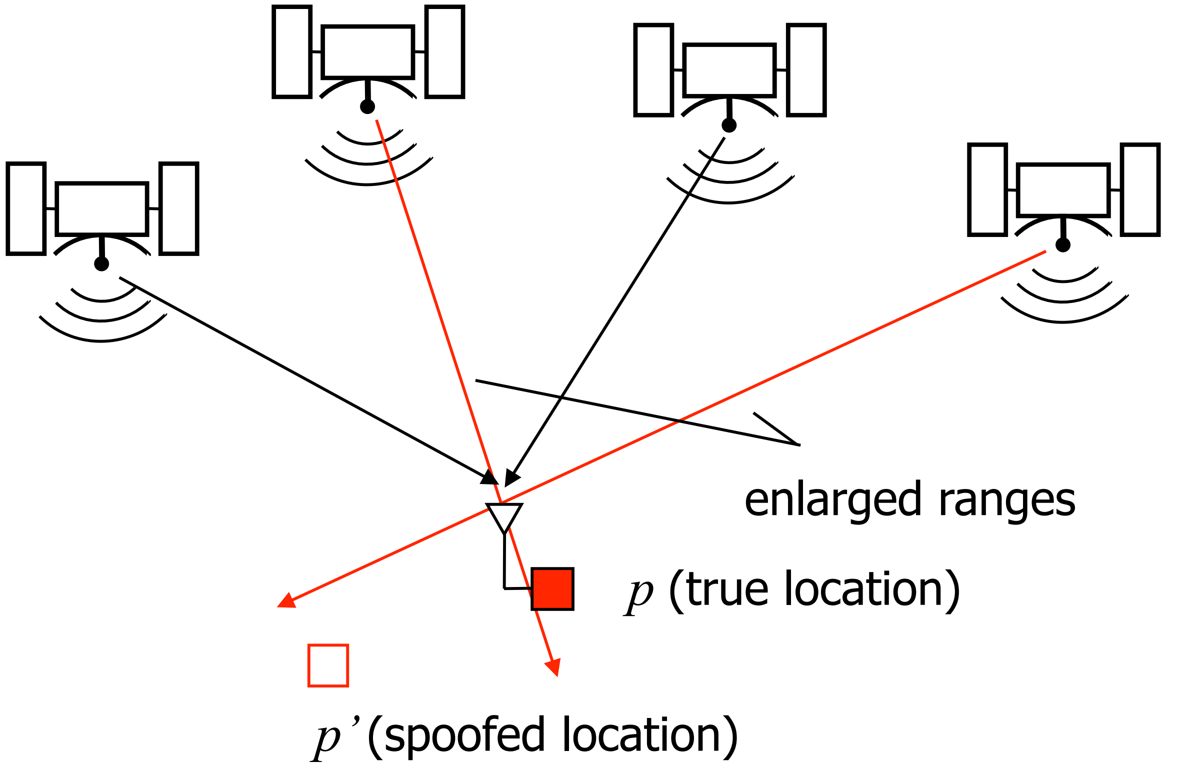


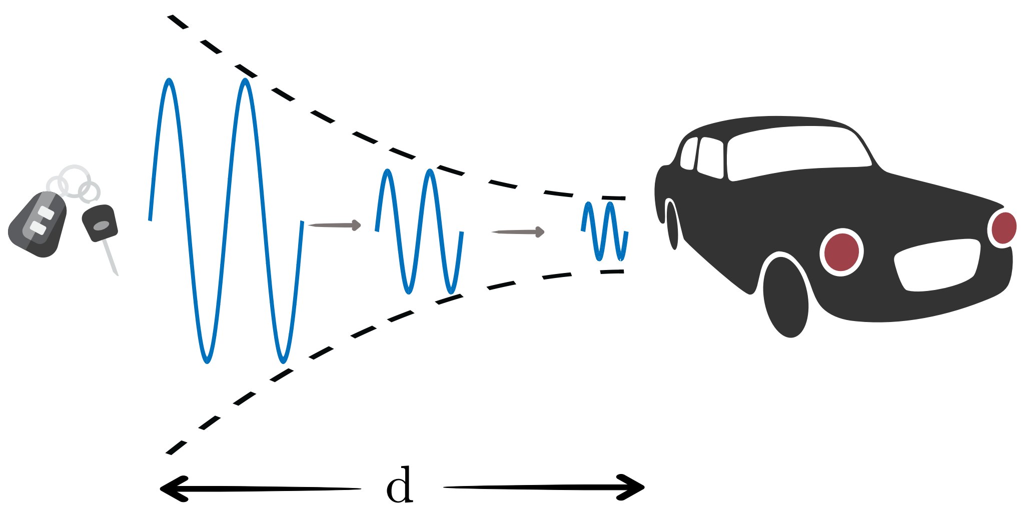

- Secure positioning requires either:
  - bidirectional communication ***or***
  - communication from the device to the infrastructure

# Secure Proximity Verification

# Recommended Readings

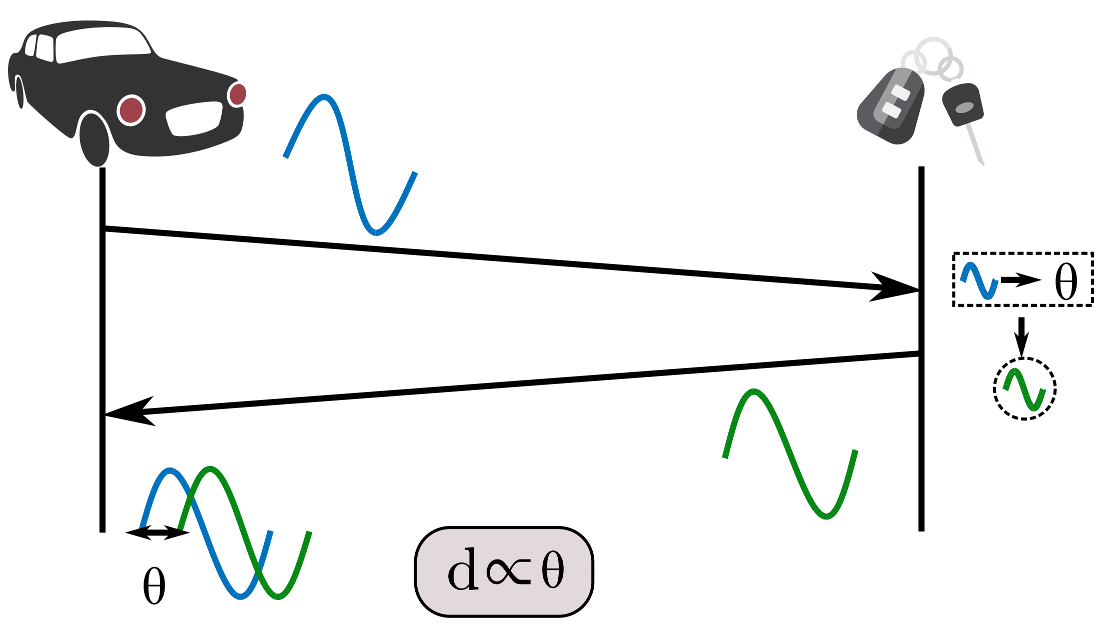
- **Are We Really Close? Verifying Proximity in Wireless Systems.** *Aanjhan Ranganathan, Srdjan Capkun* (IEEE Security and Privacy Magazine)
- **Distance Bounding Protocols.** *Stefan Brands and David Chaum.* (extended abstract - Eurocrypt 1993)
- **Verifiable Multilateration.** *S. Capkun, J. P. Hubaux.* **(**Secure positioning in wireless networks, IEEE Journal on Selected Areas in Communications: Special Issue on Security in Wireless Ad Hoc Networks, February 2006.)

# Estimating Proximity




## Received Signal Strength

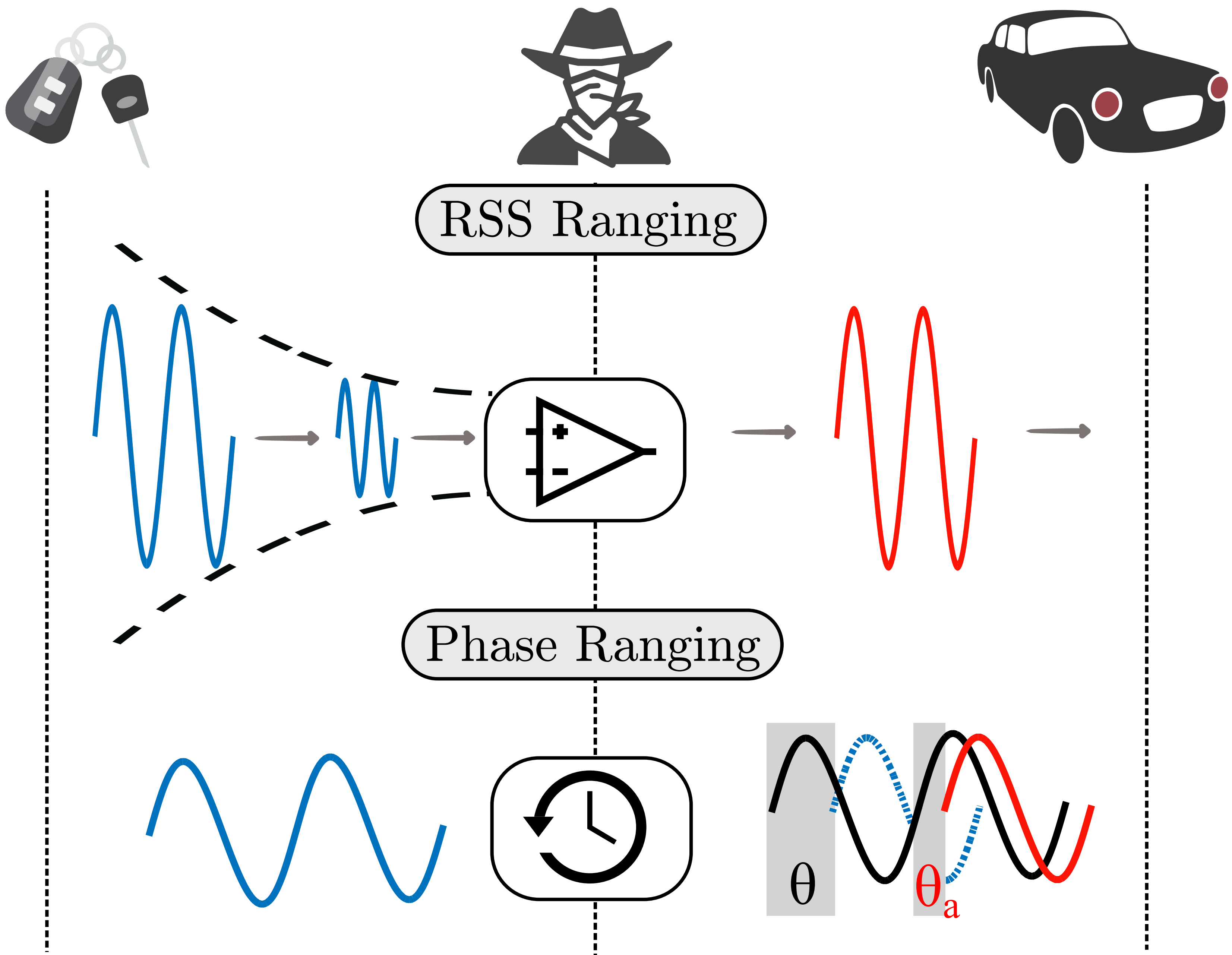
$$d = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t G_r}{P_r}}$$




## Carrier Phase Ranging

$$d = \frac{c}{2 \cdot f} \cdot (\frac{\theta}{2\pi} + n)$$

# Attacking Proximity

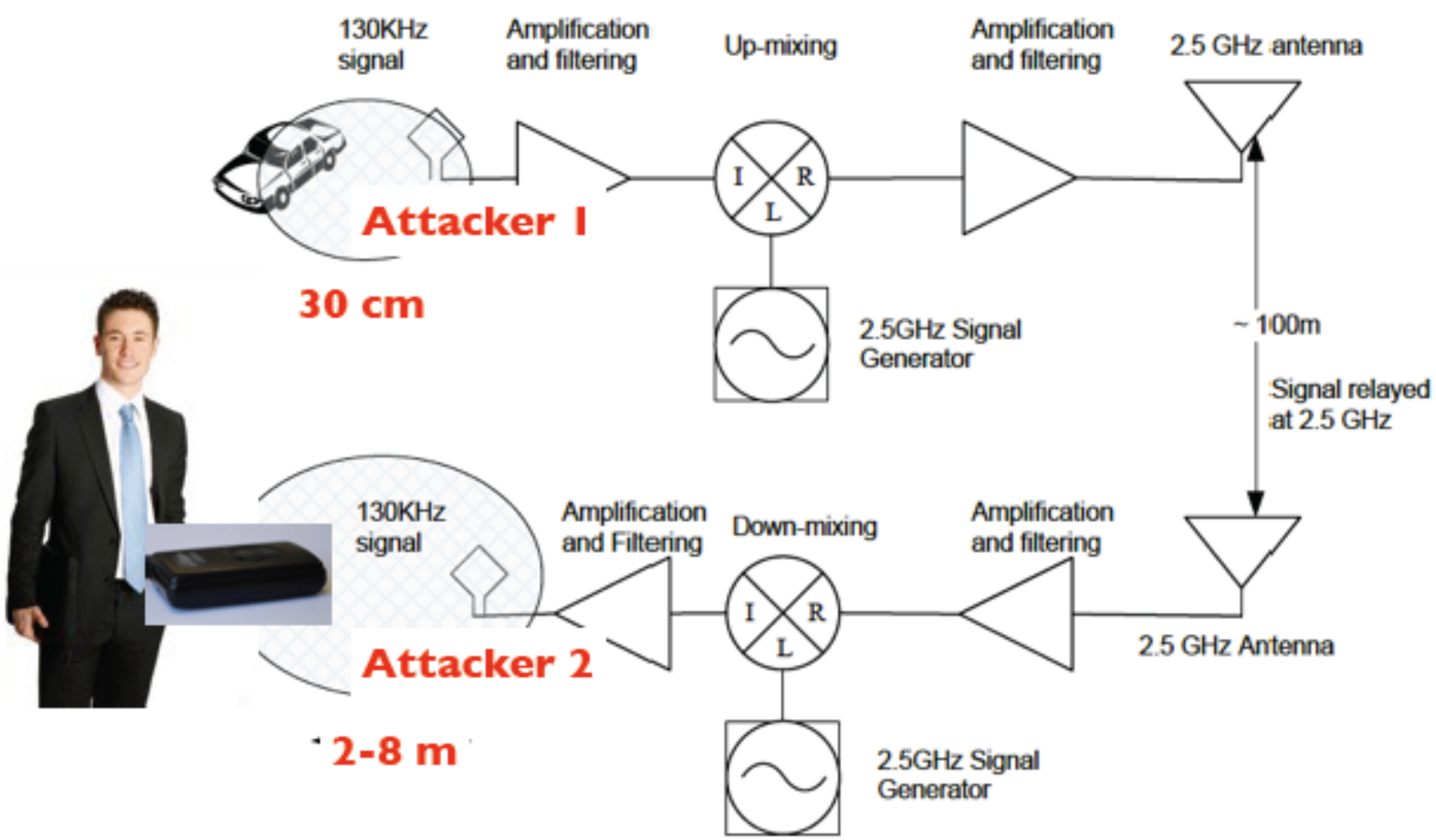


# Example: PKES

(deployed by all major car manufacturers)

PKES: Key is “in pocket” - car opens when the key is *close to the car*

- *Relay attack [FrancillonNDSS11]*

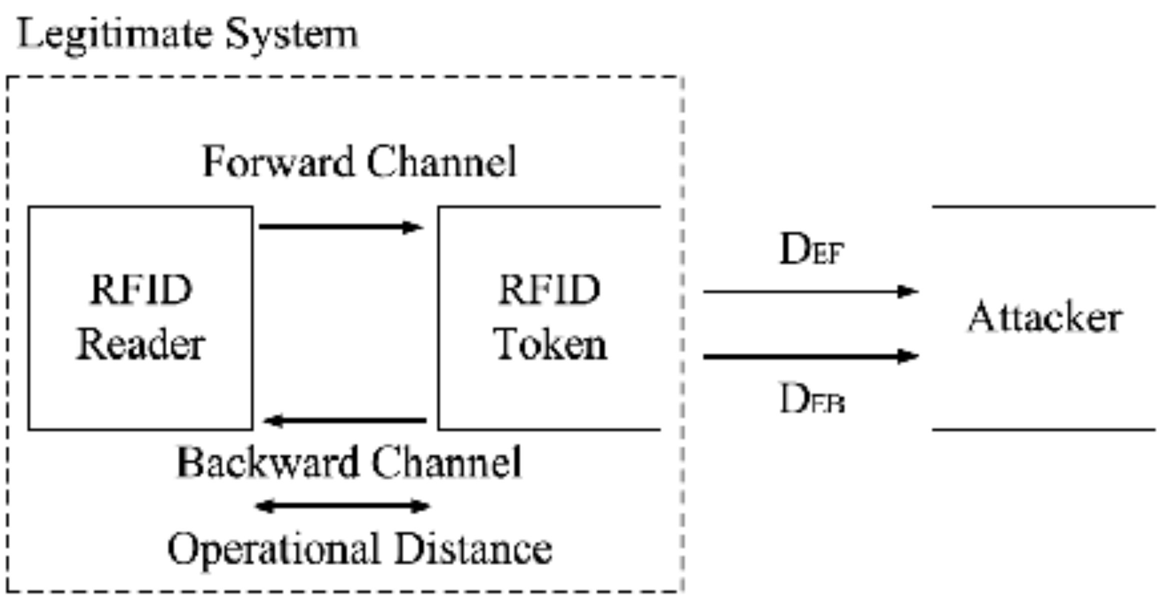



- Tested on 10 car models from 8 manufacturers
- Manufacturers are now redesigning Entry and Start Systems

# Example: RFID / NFC communication

Do LF/HF RFID/NFC systems provide guarantees on the communication range?

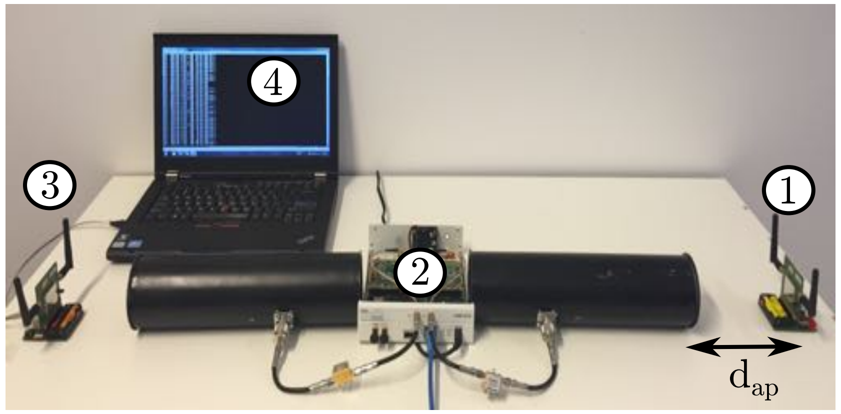
- HF RFID, ISO 14443 and ISO 15693 [Hancke10]

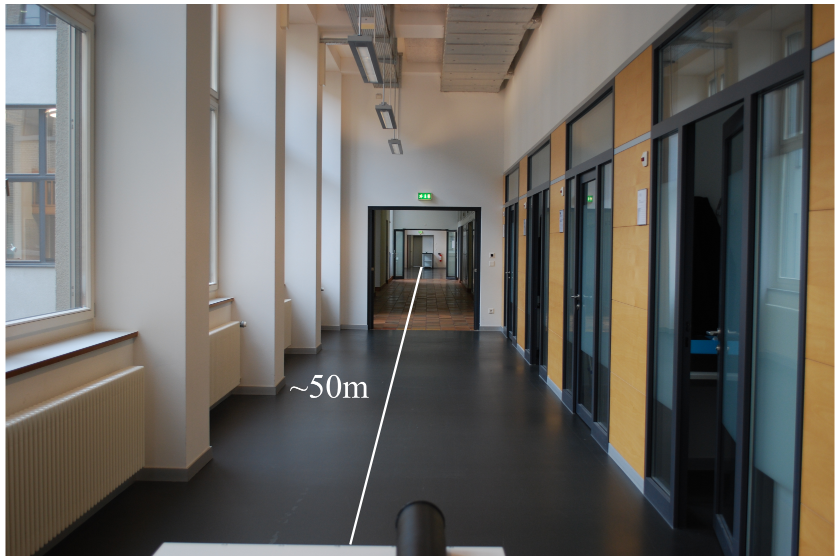


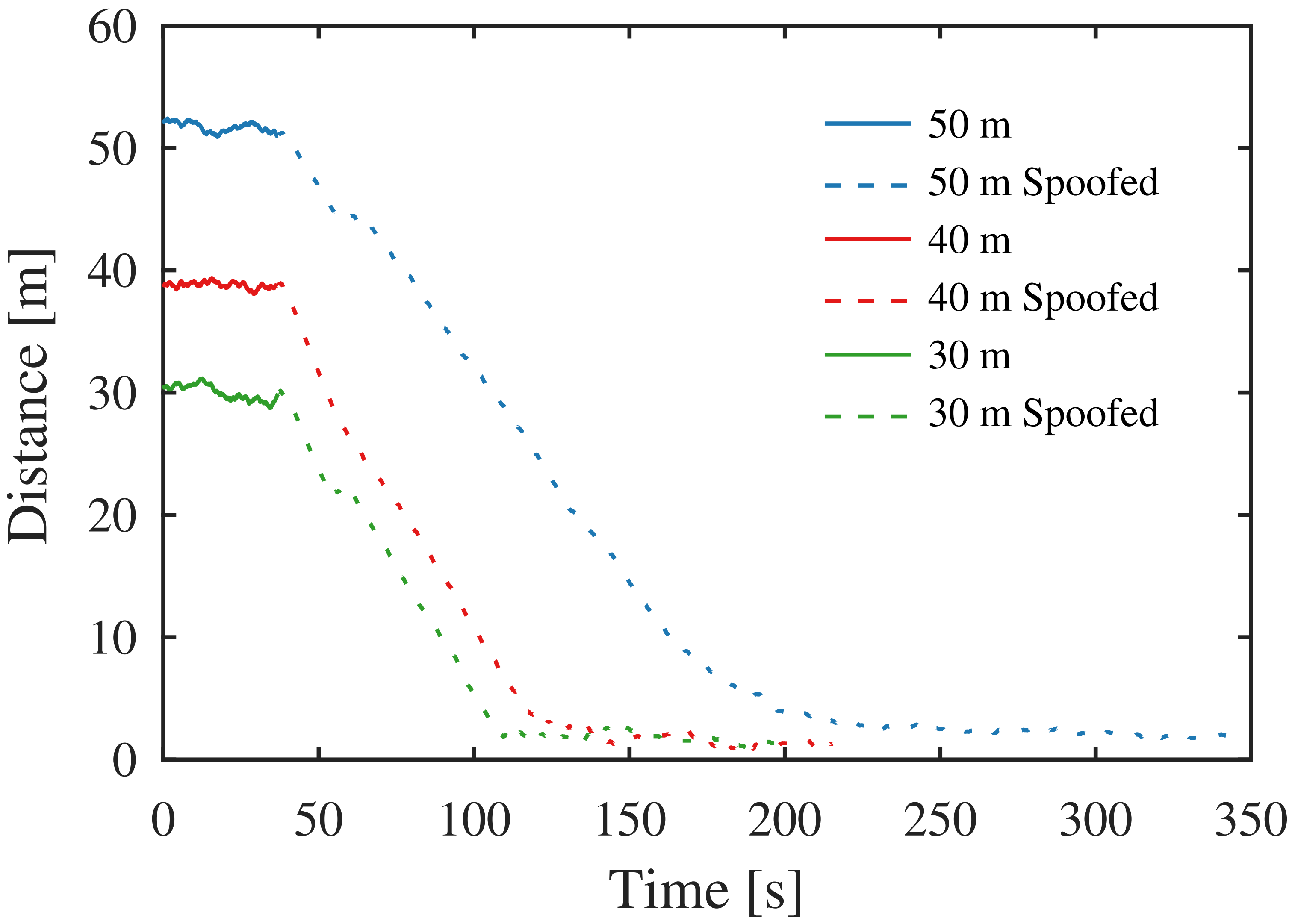

| | ISO 14443A | ISO 14443B | ISO 15693 |
|---|---|---|---|
| Entrance hall | | | |
| 1 m | FB | FB | FB |
| 2 m | FB | FB | FB |
| 3 m | Fx | xB | Fx |
| 4 m | Fx | xx | Fx |
| 5 m | Fx | xx | Fx |
| Lab corridor | | | |
| 1 m | FB | FB | FB |
| 2 m | FB | FB | FB |
| 3 m | FB | FB | Fx |
| 4 m | Fx | xB | Fx |
| 5 m | Fx | xx | Fx |

Table 1: Eavesdropping results: F – Forward channel recovered, B – Backward channel

# Attacking Phase Ranging Systems



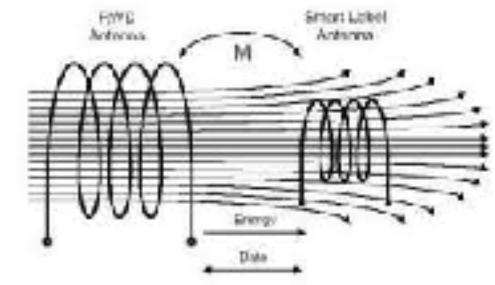




**Hildur Ólafsdóttir, Aanjhan Ranganathan, and Srdjan Capkun. "On the Security of Carrier Phase-based Ranging." In *International Conference on Cryptographic Hardware and Embedded Systems*, 2017**

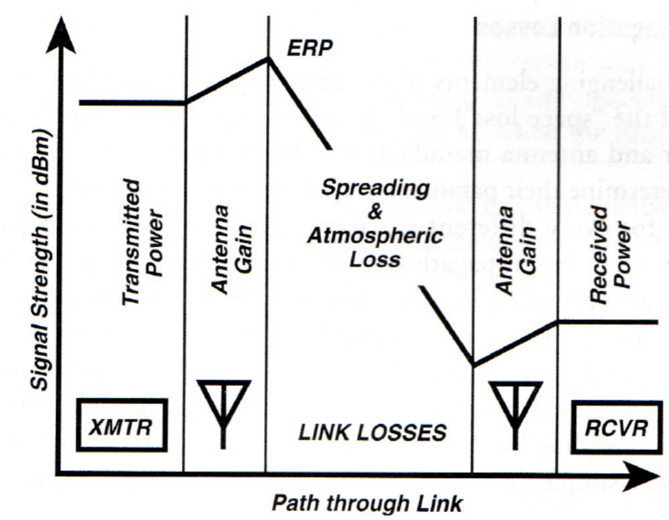
# Secure Proximity Verification?

Secure Proximity Verification

- Inductive Coupling
- Radio Communication




*Communication DOES NOT imply physical proximity.*
*(in adversarial environments)*




To calculate the received signal level (in dBm), add the transmitting antenna gain (in dB), subtract the link losses (in dB), and add the receiving antenna gain (in dB) to the transmitter power (in dBm).

©D. Adamy, A First Course on Electronic Warfare

*As shown in PKES systems, relying on the reduced communication range is either not convenient or not secure.*

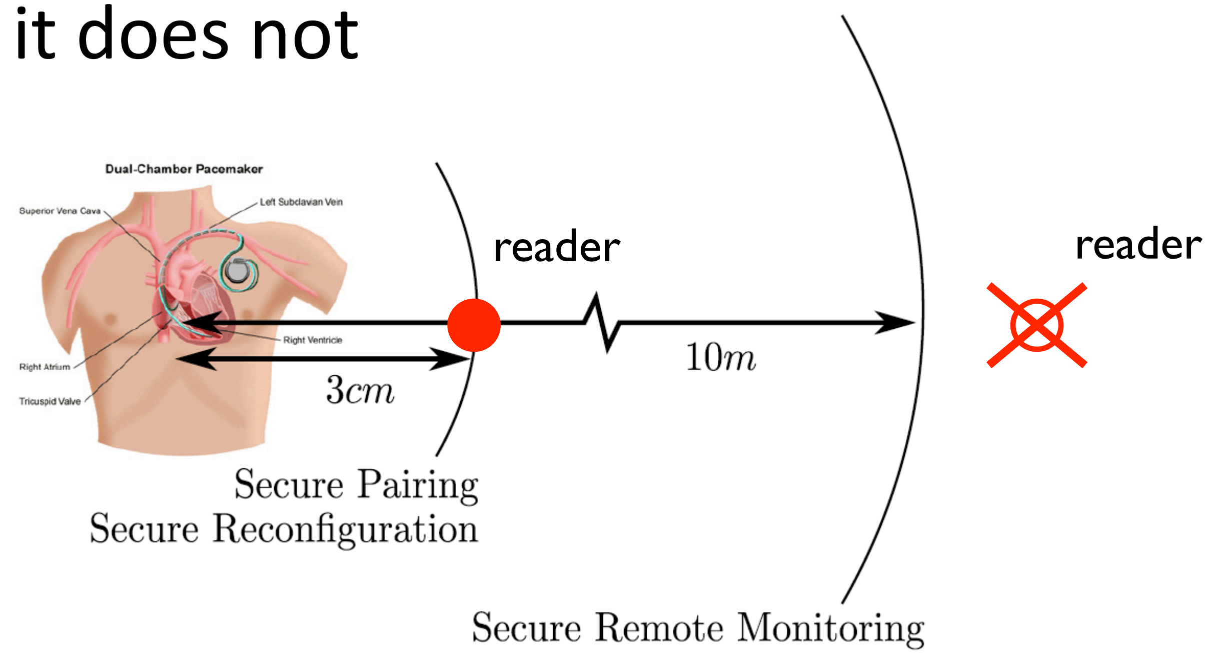
- *We need a difficult problem to hold on to.*

Solution: Secure Proximity Verification ***using secure ranging***.

# Secure Proximity Verification

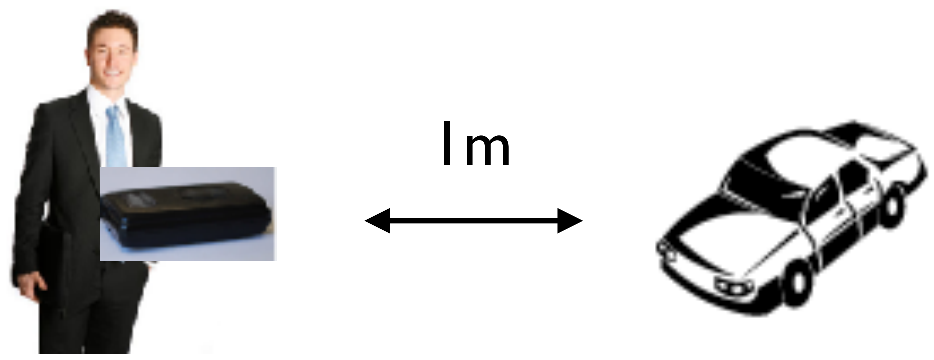
One (untrusted) device wants to *prove to be close* to another device.

- e.g., if a reader is close to the pacemaker, it gets access, otherwise it does not

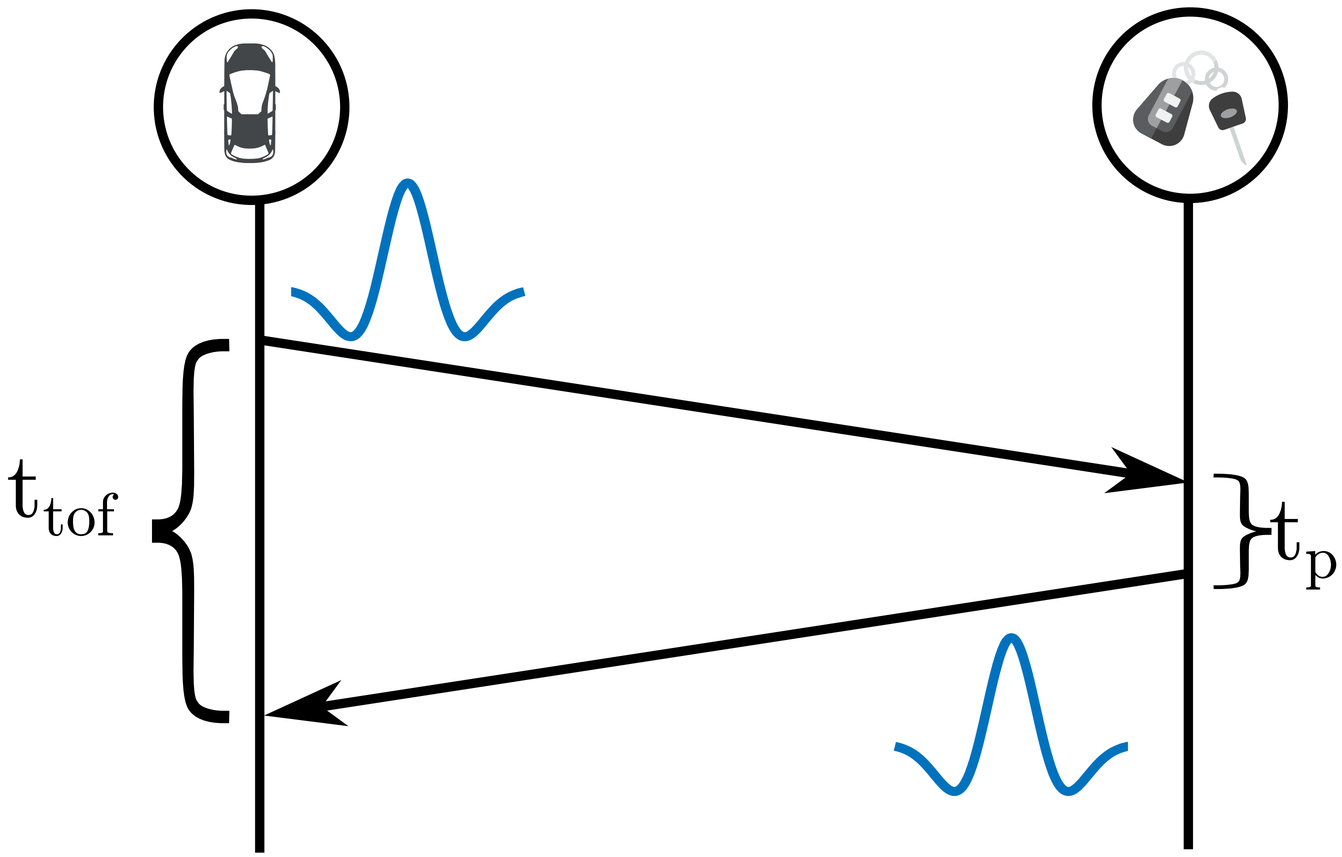



Two devices want to *verify if they are indeed close.*

- e.g., a car and a key want to verify if they are physically close



# Estimating Proximity using Time of Flight




$$d = c * (t_{tof} - t_p) / 2$$

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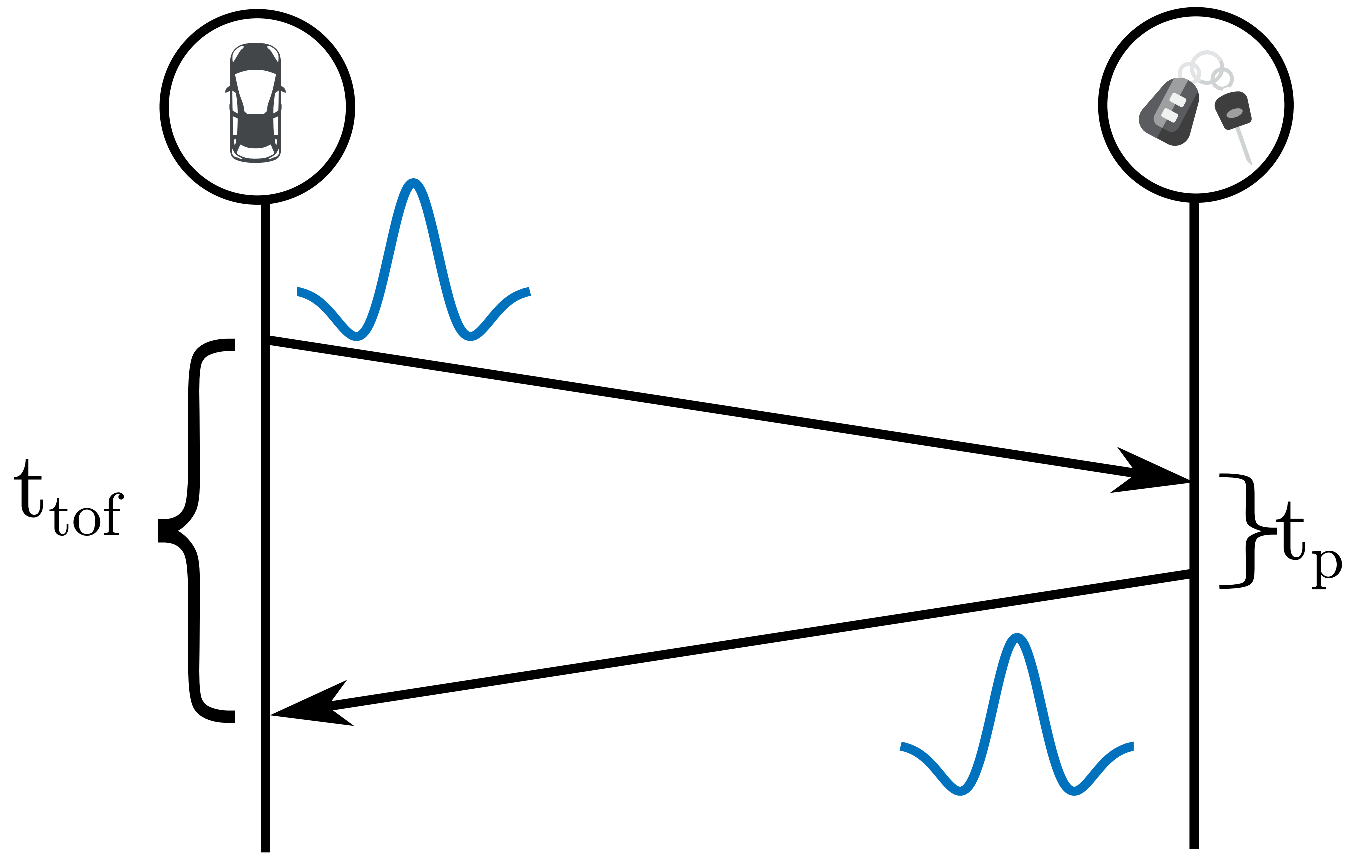


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**Can an attacker reduce time?**

**Manipulating time is harder than changing signal strength or phase**

**BUT…**

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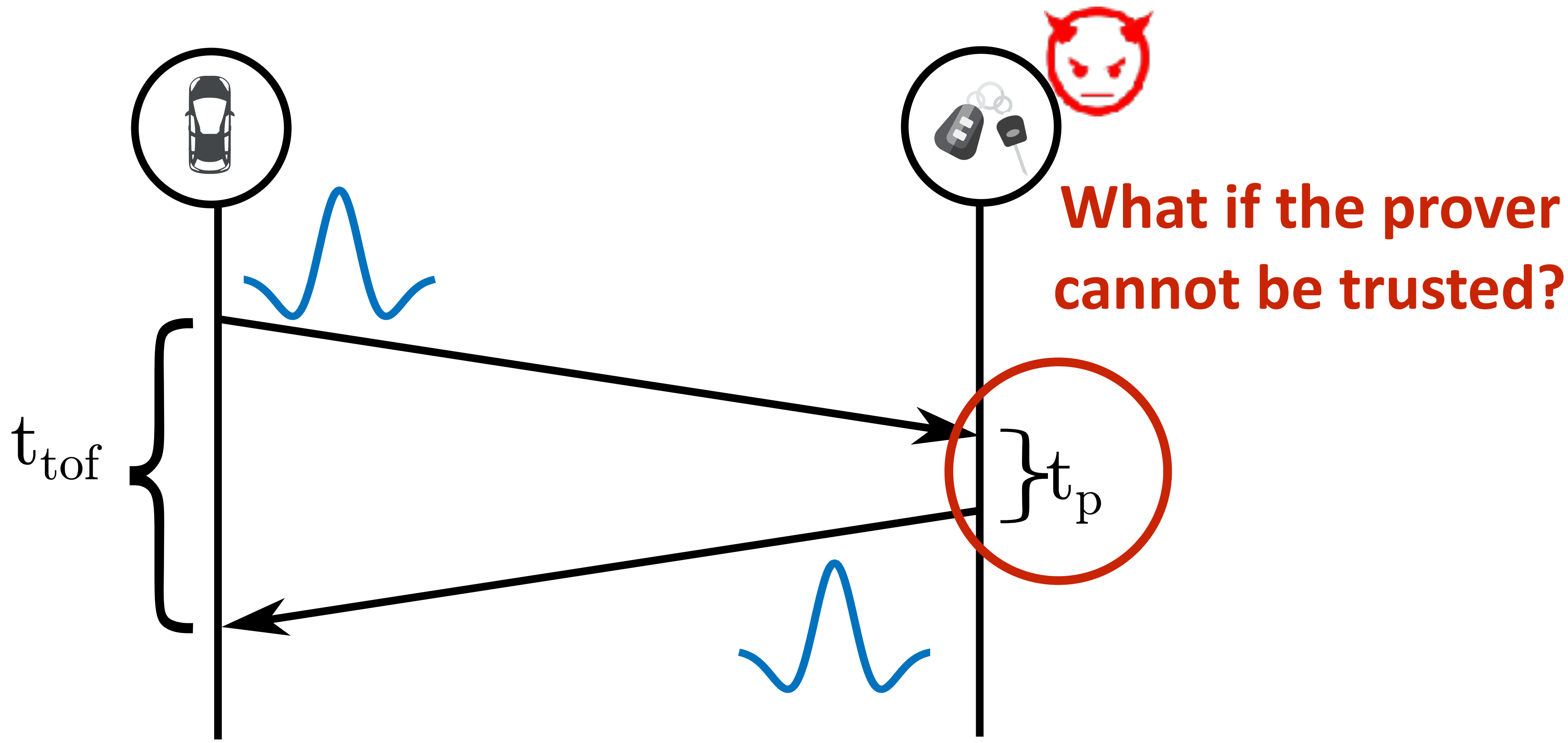


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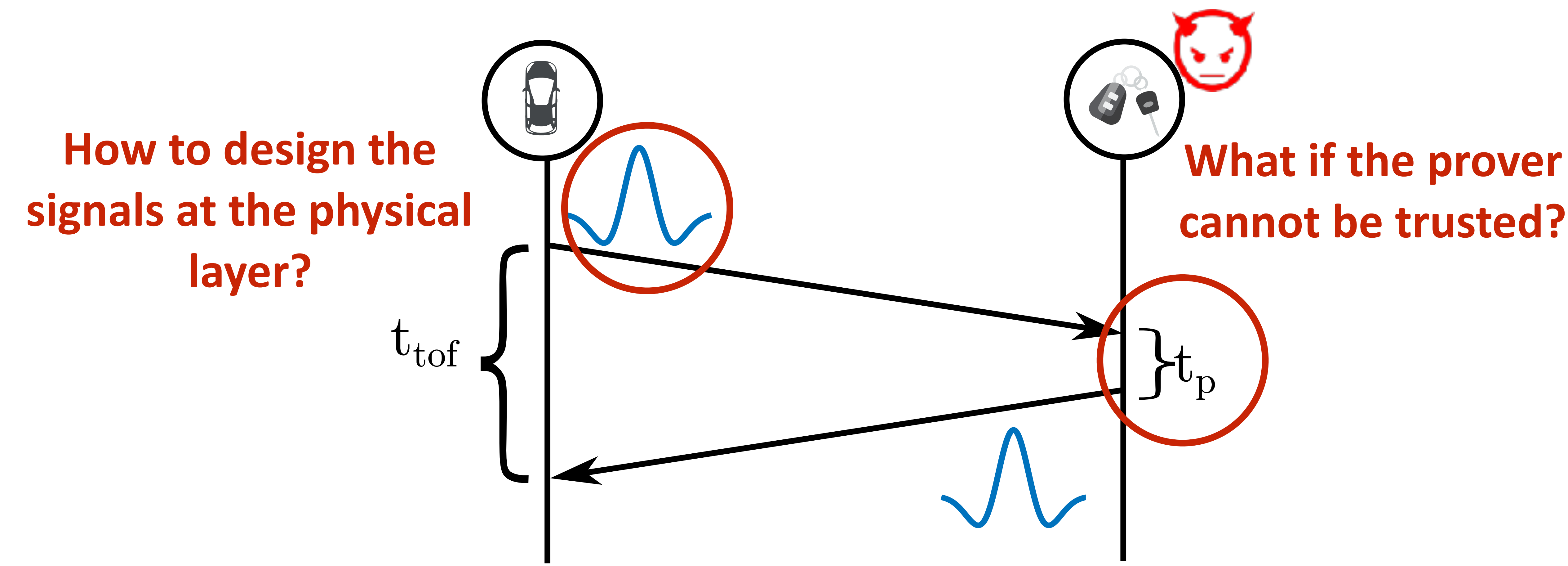


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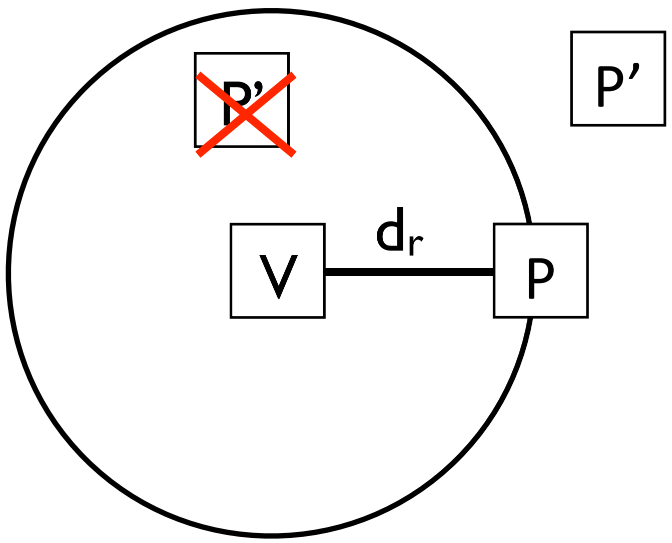
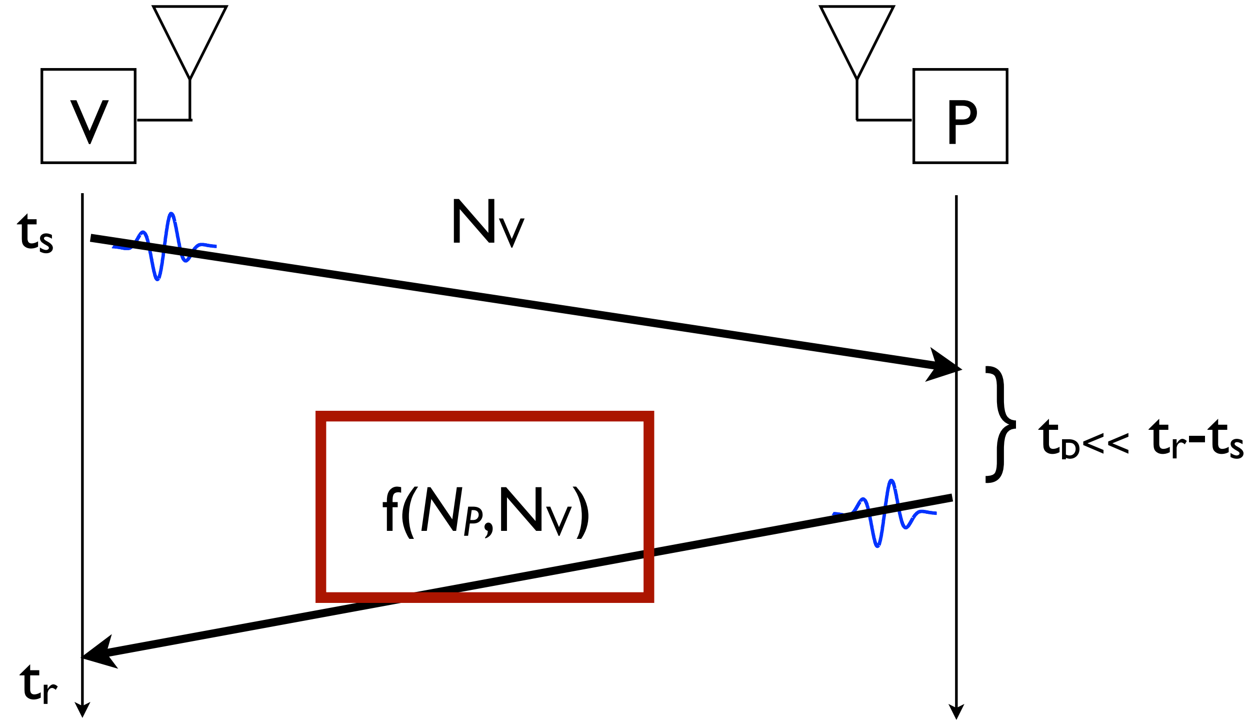
# Distance Bounding [BrandsChaum93]

Basic Idea



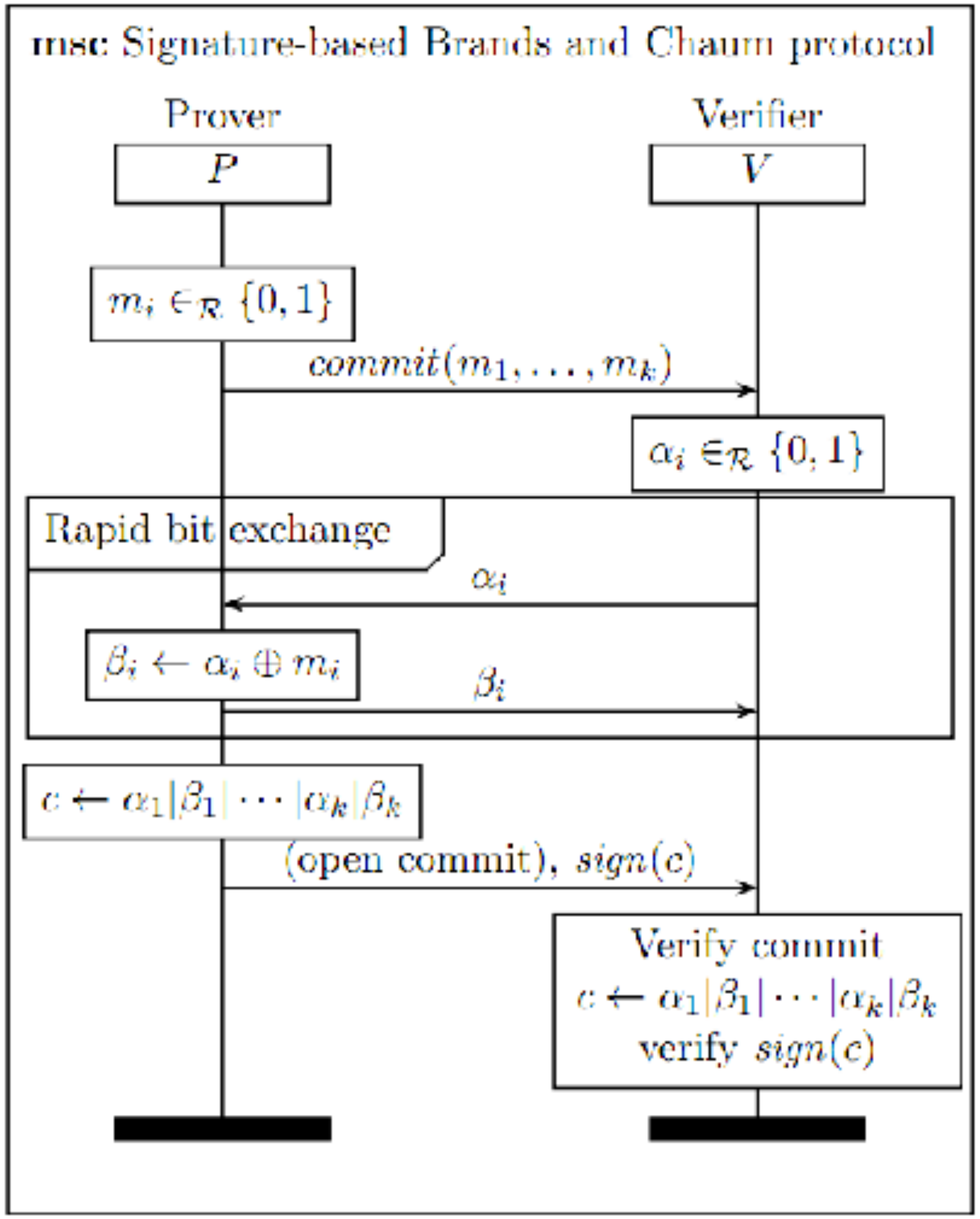




$d = (t_r - t_s - t_P)c/2$

Property:

Measured distance *d* should be an *upper bound* on the true distance $d_r$ between V and P.

# Distance Bounding [BrandsChaum93]

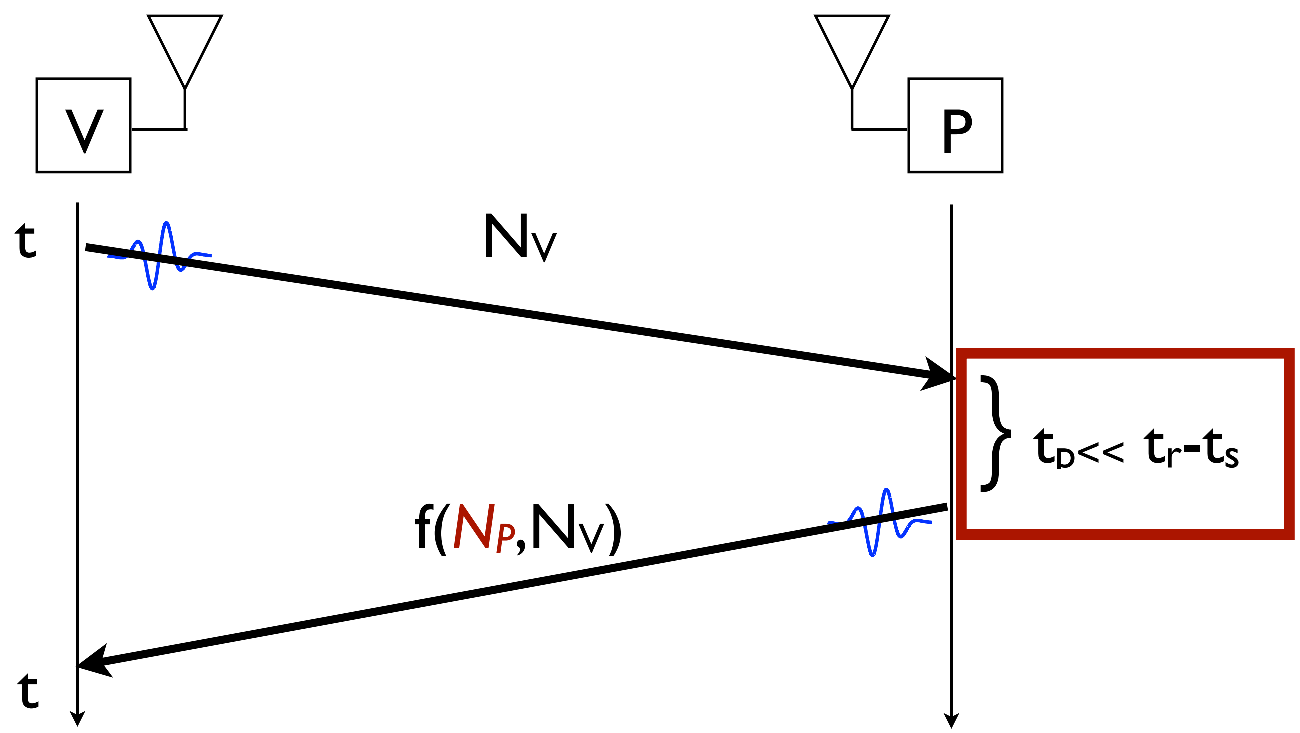


# Distance Bounding: *f() and $t_p$*

Provers should ***quickly*** *receive $N_V$, compute $f(N_V,N_P)$ and send $f(N_V,N_P)$*

- The verifier estimates prover's processing = $t_p$
- If attacker's processing = 0 then he *can cheat by $t_p/2$*
- Thus ideally $t_p$=0s, in most applications $t_p$=1-2ns (15-30cm)
- $t_p$ needs to be *stable and* ***short***

*Main assumption: we do not control the prover*

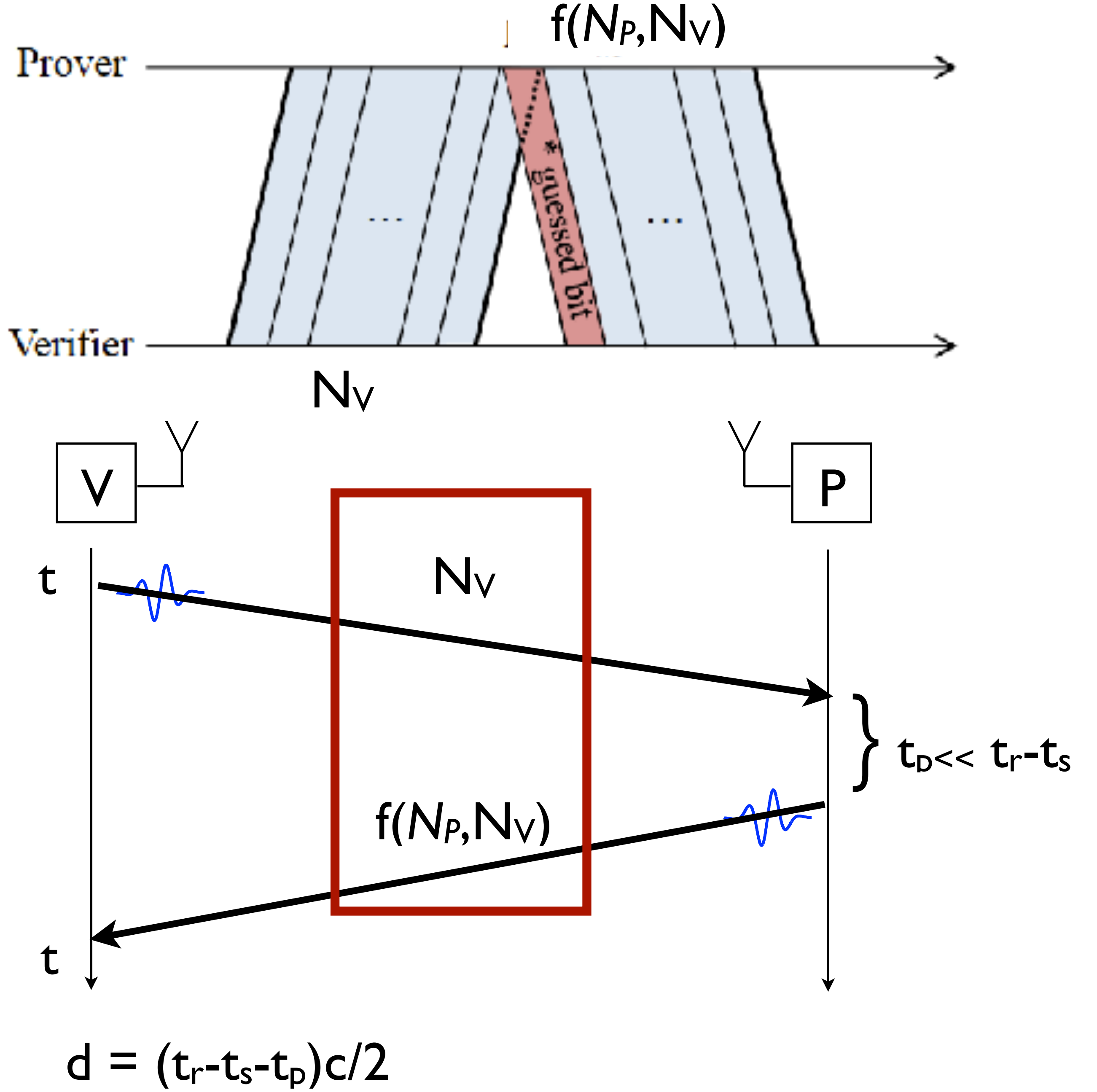



$d = (t_r-t_s-t_p)c/2$

# Distance Bounding: $N_v$

*$N_V$ and f(NV,NP) should be "short" in the # of bits* [HankeKuhn]

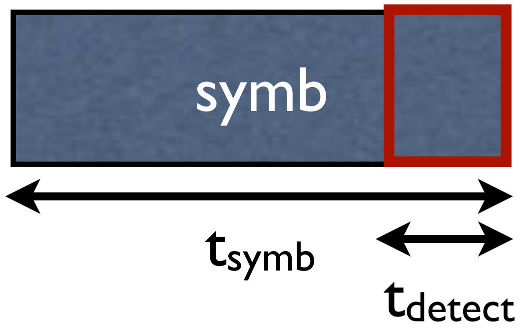
- short compared to the required accuracy / security



# Distance Bounding: *symbols*

*Assuming $|N_V|$=1bit, the symbols should be short as well*

- short compared to the required accuracy / security
- Early Detection
- Late Commit
- Note: *channel spread does not help*



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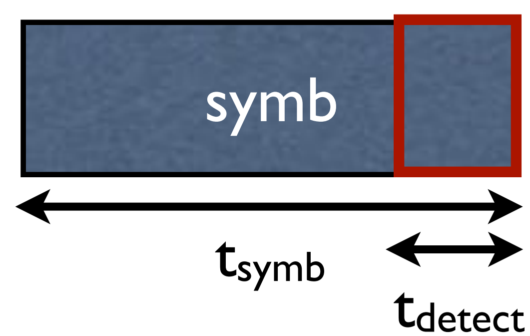


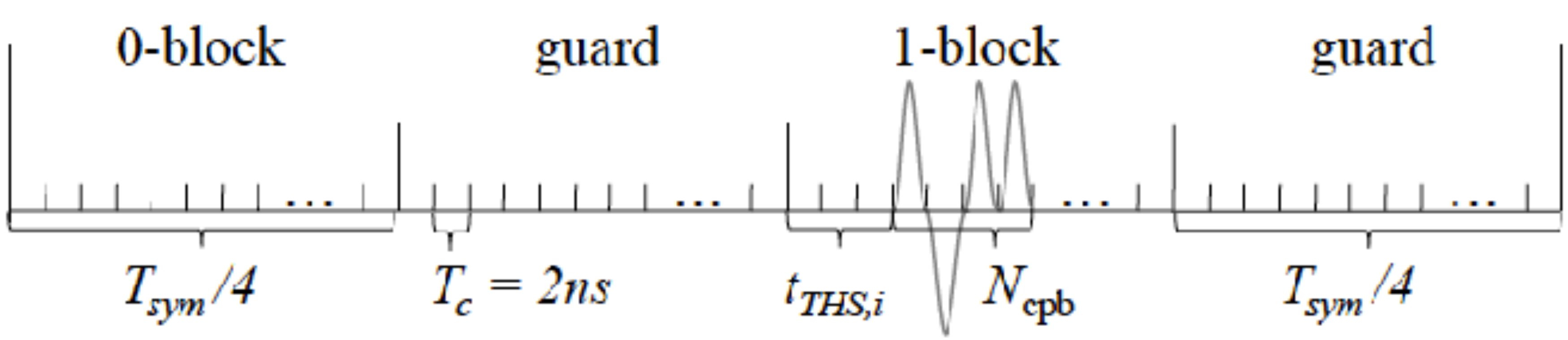
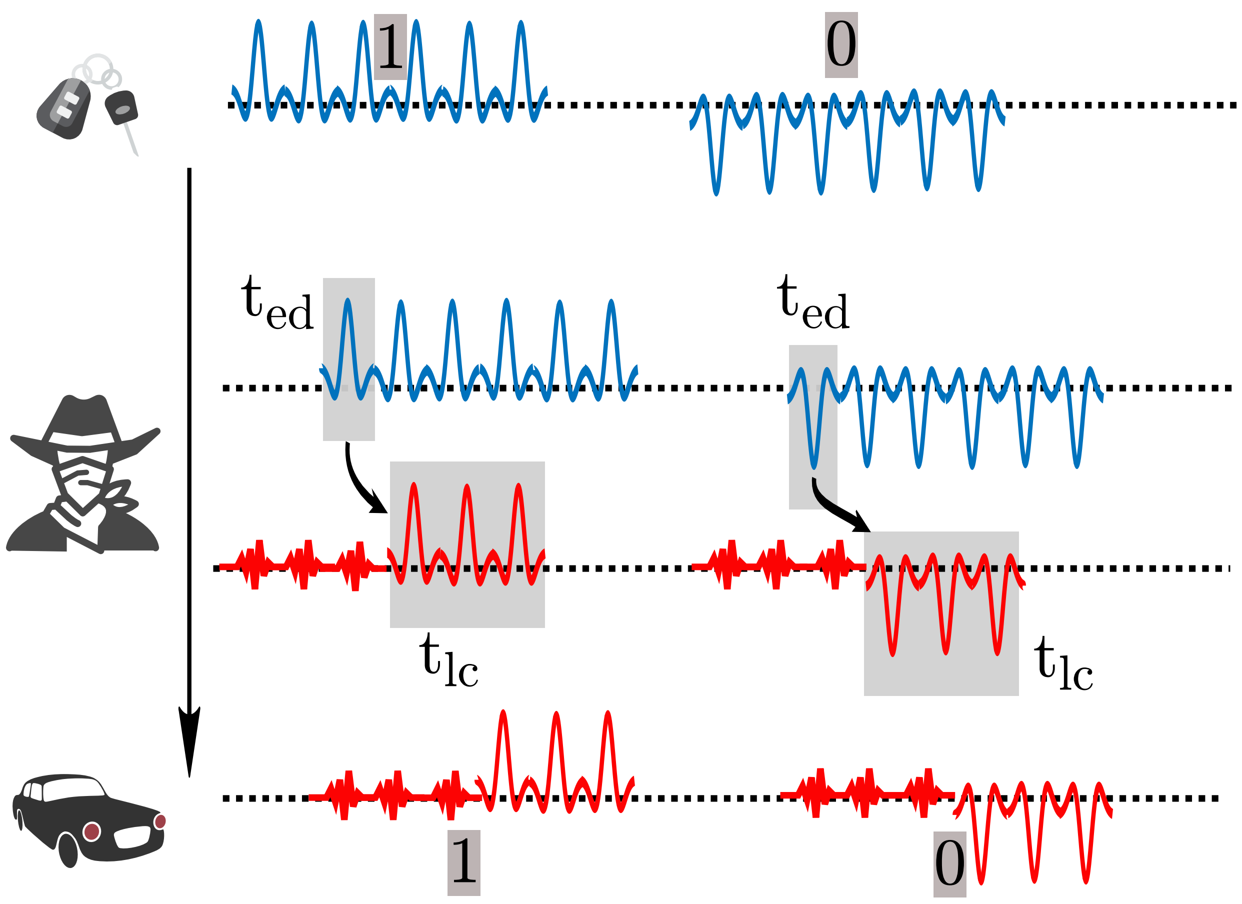




Figure 4.2: IEEE 802.15.4a data symbol structure [Poturalski2011

# Distance Bounding: *symbols*

**Early detect and late commit attacks**



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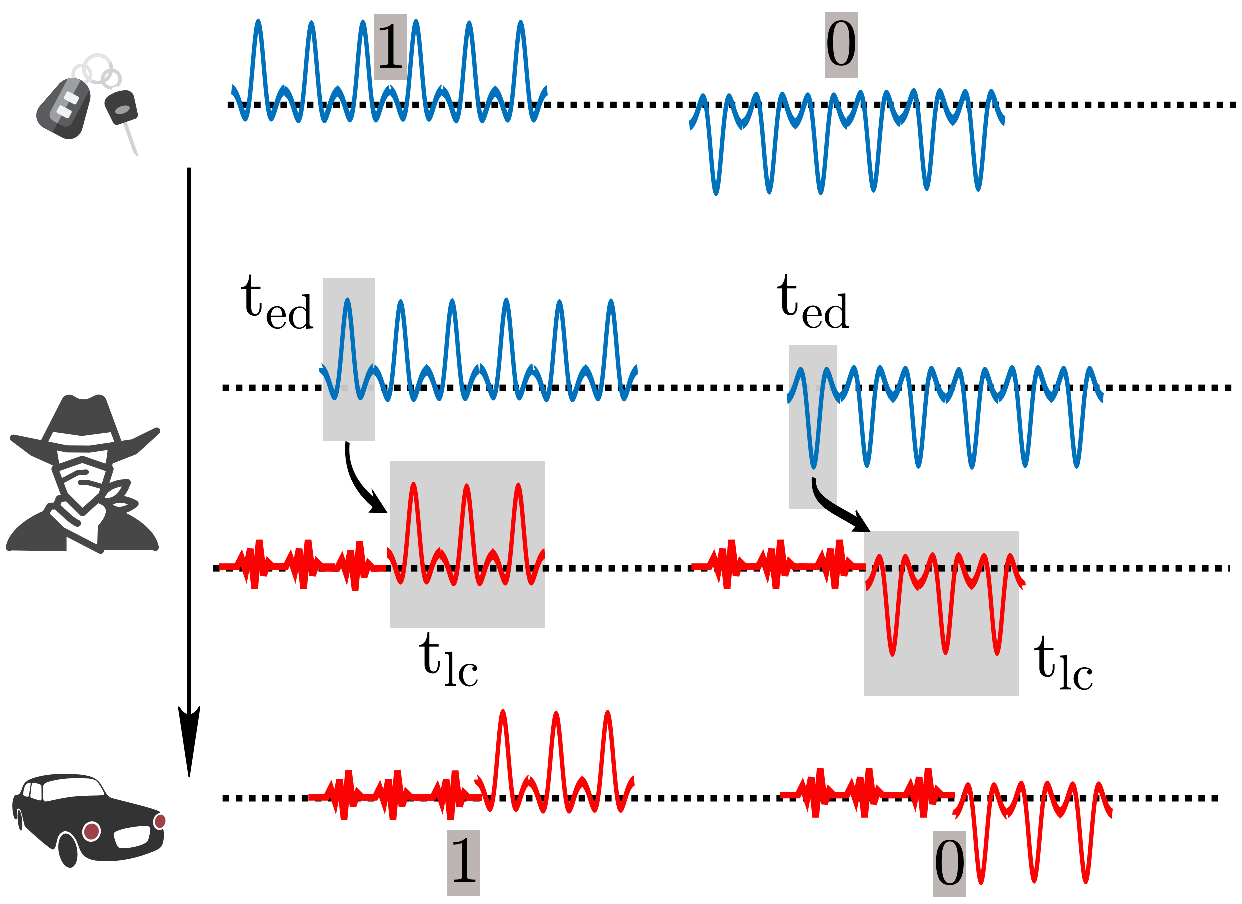


- Predicting the bit even before **completely** receiving it.

# Distance Bounding: *symbols*

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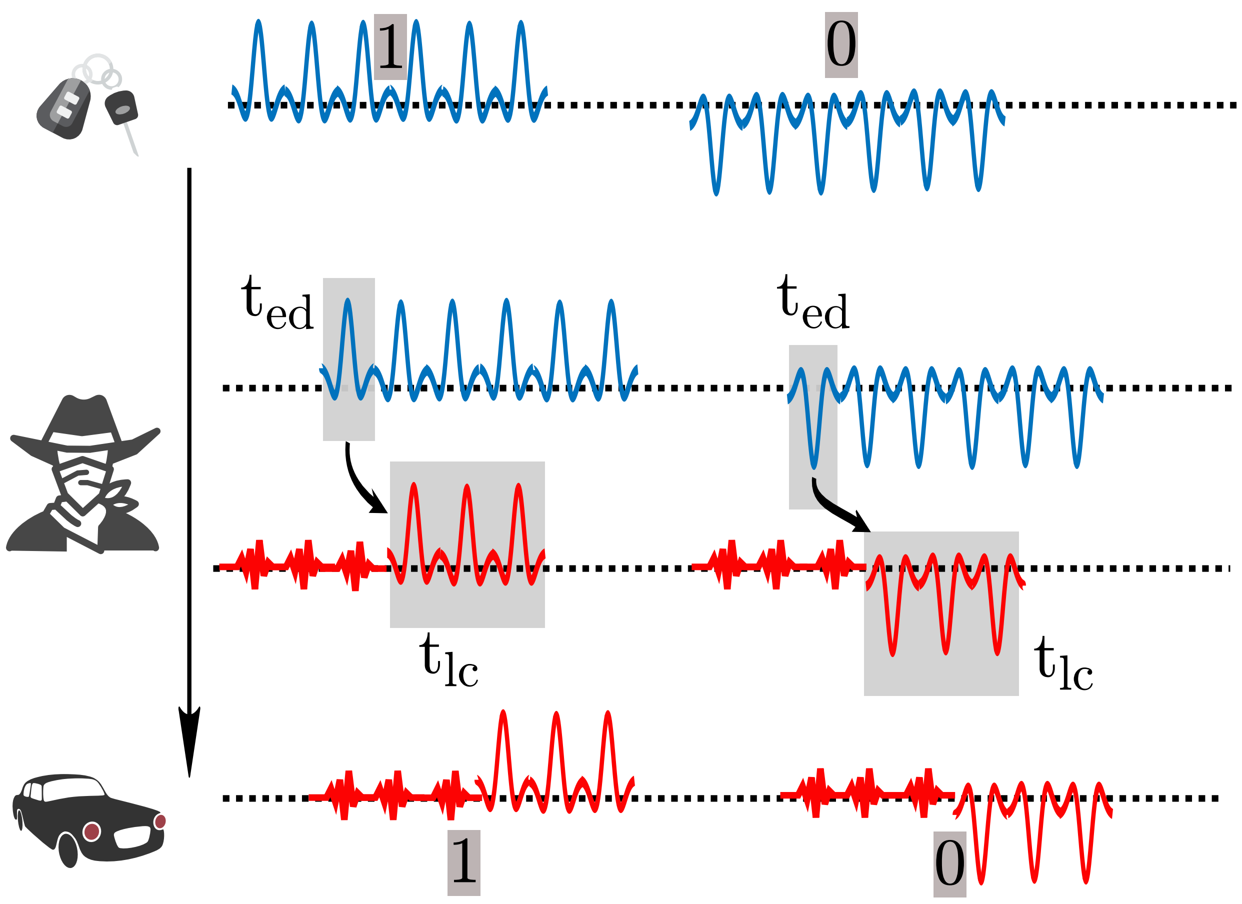


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# Distance Bounding: *symbols*

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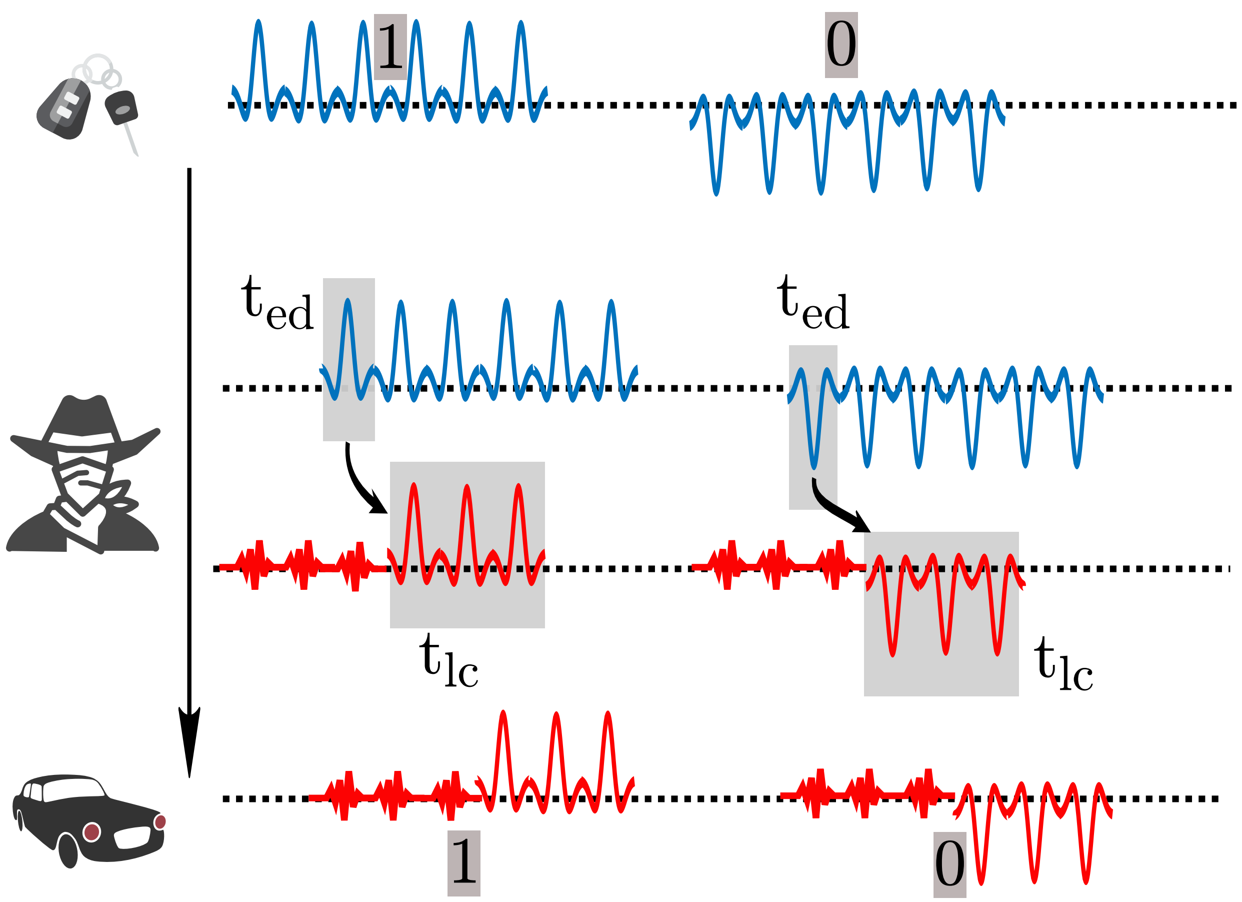


- Predicting the bit even before **completely** receiving it.
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- Transmit arbitrary signal until the symbol is **early detected**. Leverage receiver robustness.

# Distance Bounding: *symbols*

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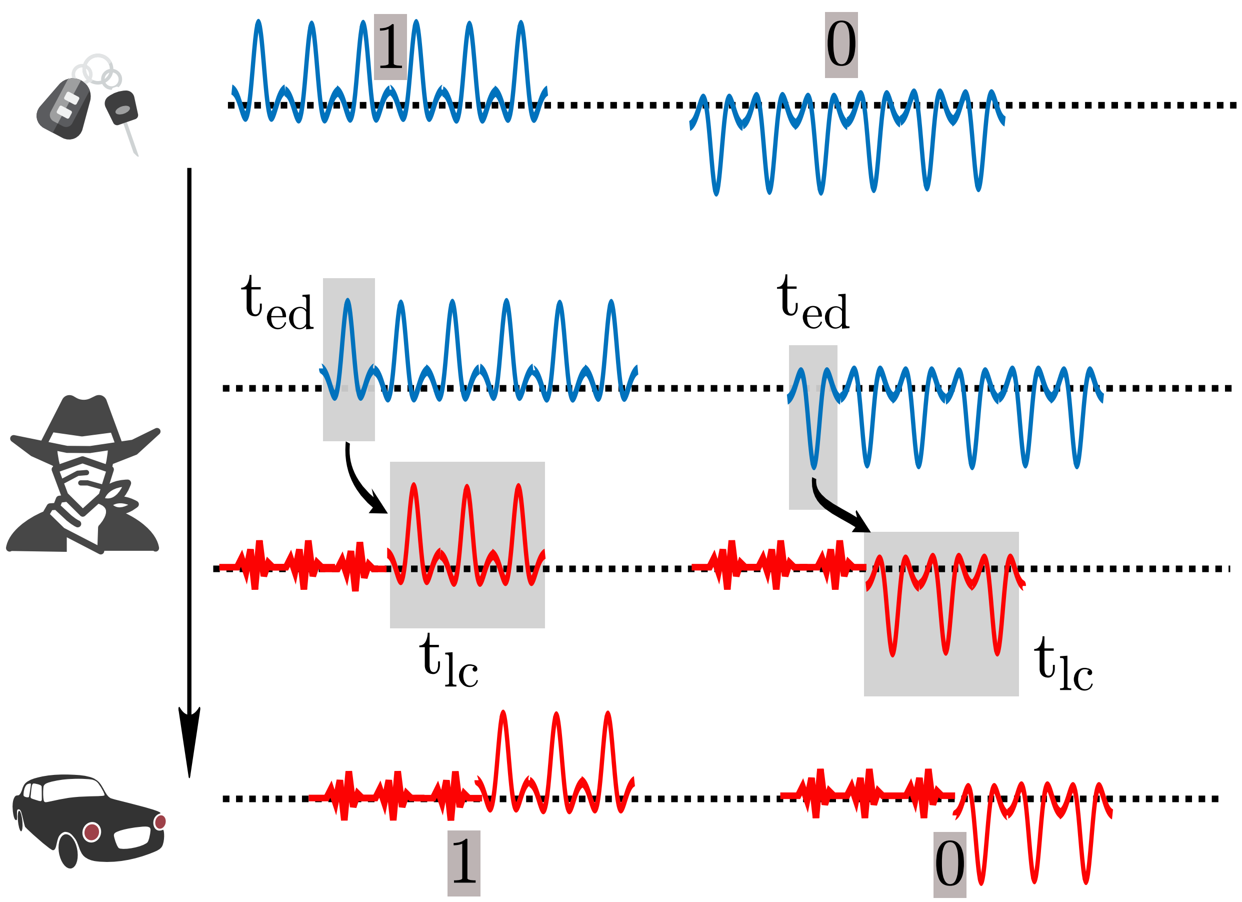



- Predicting the bit even before **completely** receiving it.
- Detecting a bit ‘1’ and ‘0’ from partially received symbols
- Transmit arbitrary signal until the symbol is **early detected**. Leverage receiver robustness.
- Short symbol length?

# Distance Bounding

## *experiments on 802.15.4a (IR UWB)*

[Poturalski2011]

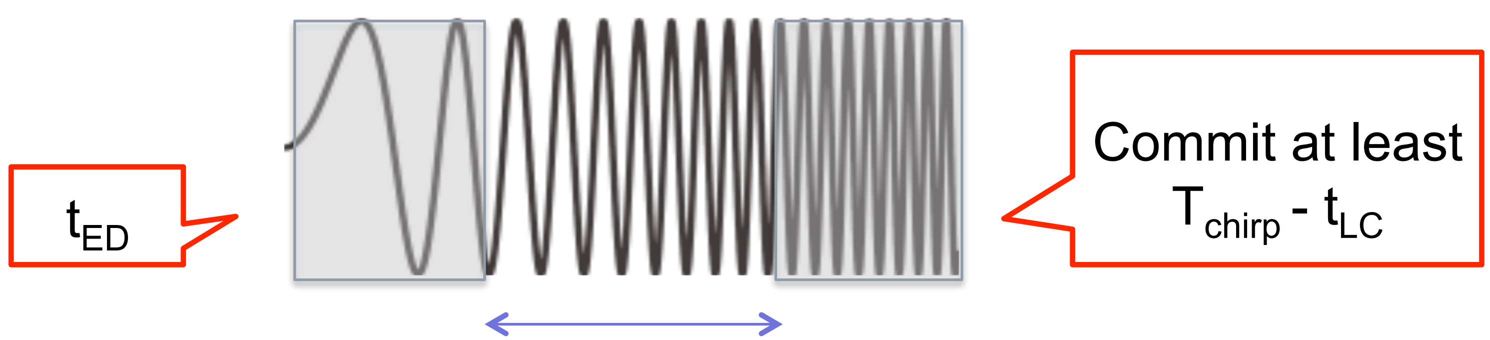
| | | No guessing | | Max. guessing gain | |
|---|---|---|---|---|---|
| | | (relay) time-gain | distance-decrease | (relay) time-gain | distance-decrease |
| **En.D. against En.D.** | | | | | |
| *Malicious Prover* | ED-only | $T_{sym}/4 + (t_{det} - t^A_{det})/2$ | 86m | $+ t^{max}_{THS}$ | + 74m |
| | LC-only | $T_{sym}/4 + t_{PLC}/2$ | 86m | $+ t^{max}_{THS}$ | + 74m |
| | ED+LC | $T_{sym}/2 + (t_{PLC} + t_{det} - t^A_{det})/2$ | 171m | $+ t^{max}_{THS}$ | + 74m |
| *Relay Attack* | ED+LC | $T_{sym}/2 + t_{PLC} - t^A_{det}$ | 171m | $+ 0$ | + 0m |
| **Rake against En.D.** | | | | | |
| *Malicious Prover* | ED-only | $T_{sym}/2 + (t_{det} - t^A_{det})/2$ | 162m | $+ T_{sym}/4 + t^{max}_{THS}$ | + 151m |
| | ED+LC | $3/4 \cdot T_{sym} + (t_{PLC} + t_{det} - t^A_{det})/2$ | 248m | $+ T_{sym}/4 + t^{max}_{THS}$ | + 151m |
| *Relay Attack* | ED+LC | $T_{sym} - t^{max}_{THS} + t_{PLC} - t^A_{det}$ | 251m | $+ T_{sym}/2 + 2 \cdot t^{max}_{THS}$ | + 302m |
| | ED-only | $T_{sym}/2 - t^{max}_{THS} - t^A_{det}$ | 79m | $+ T_{sym}/2 + 2 \cdot t^{max}_{THS}$ | + 302m |
| **Rake against Rake** | | | | | |
| *Malicious Prover* | ED-only | $(t_{det} - t^A_{det})/2$ | 5m | $+ T_{sym}/4 + t^{max}_{THS}$ | + 151m |
| | LC-only | $t_{PLC}/2$ | 5m | $+ T_{sym}/4 + t^{max}_{THS}$ | + 151m |
| | ED+LC | $(t_{det} + t_{PLC} - t^A_{det})/2$ | 10m | $+ T_{sym}/2 + t^{max}_{THS}$ | + 228m |
| *Relay Attack* | ED+LC | $t_{PLC} - t^A_{det}$ | 10m | $+ 0$ | + 0m |

Table 4.2: Upper-bound on (relay) time-gain and (relay) distance-decrease of various PHY attacks in various "adversarial receiver against honest receiver" configurations. The left column presents conservative attacks, that work with 100% success probability. The right column presents the maximal additional time-gain/distance-decrease that can be achieved by combining PHY attacks and guessing attacks (when time guessing probability approaches the guessing probability of pure guessing attacks). Time-gain is expressed in terms of $T_{sym}$ – data symbol duration, $t_{det} = 48\text{-}60ns$ – detection time of honest receivers without ED-countermeasure, $t^A_{det}$ – detection time of the adversary, $t_{PLC} < t_{det}$ – pulse LC delay, $t^{max}_{THS}$ – maximum time-hopping offset. The distance-decrease is shown for the IEEE 802.15.4a mandatory modes and delay values that maximize the distance-decrease.

# Distance Bounding: *symbols*

*Chirp SS ranging (802.15.4) systems strongly affected**

- long symbol lengths allow for simple ED and LC attacks
- Early Detection
- Late Commit




$$t_{GAIN} = t_{LC} - t_{ED} - t_{HW}$$

$$D = c \times t_{GAIN}$$

Aanjhan Ranganathan, Boris Danev, Aurélien Francillon, and Srdjan Capkun. "Physical-layer attacks on chirp-based ranging systems." (WiSec 2012)

# Realization of RF Distance Bounding:

## *Processing Function* *$f(N_v,N_p)$*

f(Nv,Np) is computed by the prover:

- takes as input Nv (received from the verifier)
- takes as input Np (locally generated by the prover)
- Should allow that the prover: *receives Nv, computes and outputs f(Nv,Np)* **in a short time (few ns)**

***DB protocols in the literature:***

[BethDesmedt] sign($N_V$); h($N_V$); mac($N_V$); E($N_V$); ... => $t_p$ >> ns

[BrandsChaum, *CapkunInfocom05*, ...] *XOR* => $t_p$ = ?

[HanckeKuhn, *TippenhauerESORICS09*, ...] *bit comparison* => $t_p$ = ?

> 20 proposed protocols, not one was ***fully*** implemented

*Can the proposed DB protocols be realized?*

# Realization of RF Distance Bounding:
## *Processing Function f($N_v$,$N_p$)*

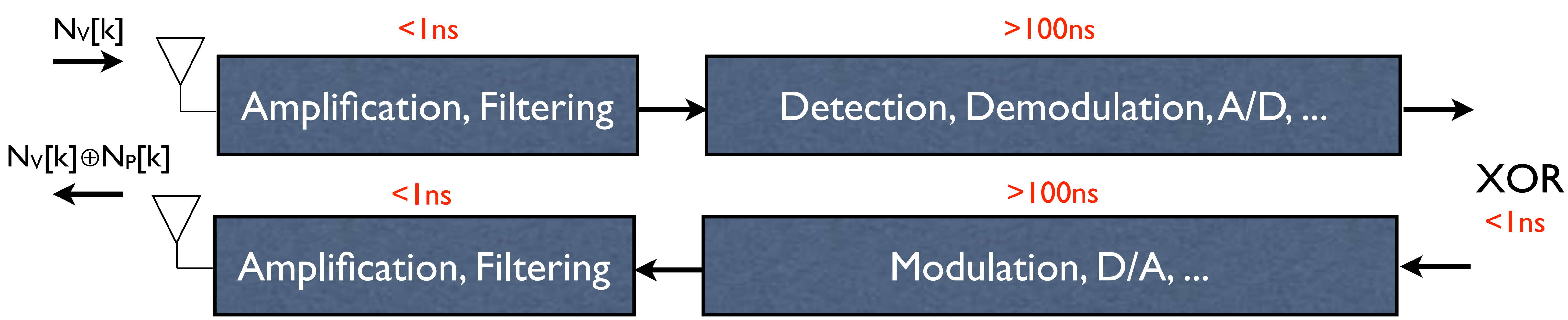
[BethDesmedt] sign(); h(); mac(); E(); … => $t_p$ >> ns

[**BrandsChaum**, …] *XOR* => $t_p$ = ? (nx100ns ?)

[**HanckeKuhn**, …] *bit comparison* => $t_p$ = ? (nx100ns ?)

[RasmussenSec09, …] *CRCS (analog modulation)* => $t_p$ < 1ns

… > 20 proposed protocols




*Can we use functions that require interpretation (demodulation) Nv ?*

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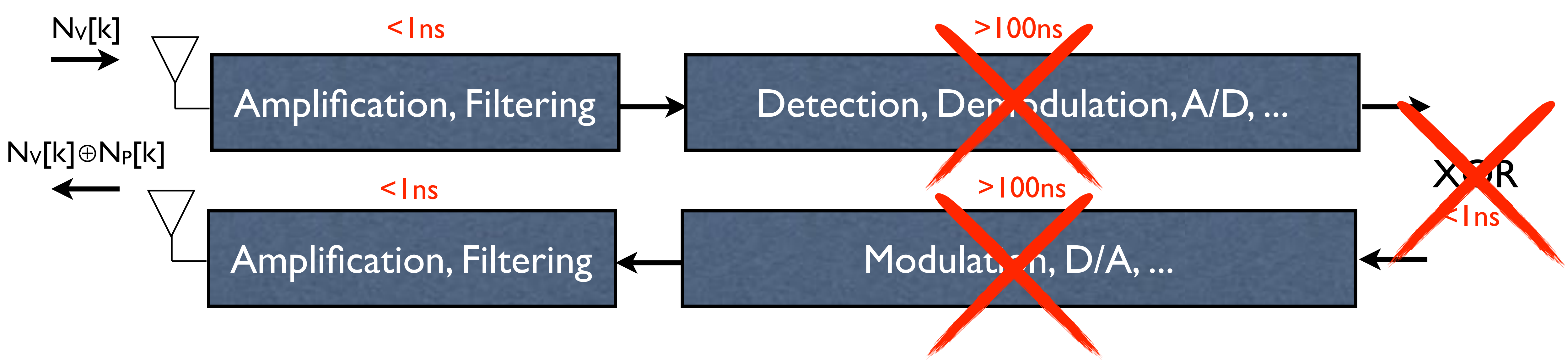


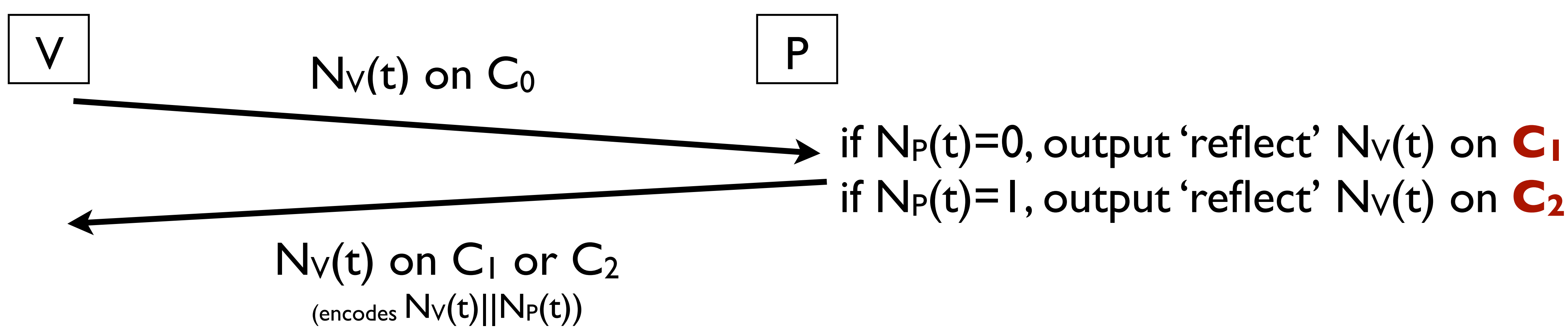

*Can we use functions that require interpretation (demodulation) Nv ?*

# A new Function: CRCS

Our approach: *Challenge Reflection with Channel Selection*

- Prover does not interpret Nv
- All *time-critical* processing is done in *analog*
- Verifier does "all the work"

Main idea ($C_0$,$C_1$,$C_2$ are channels)



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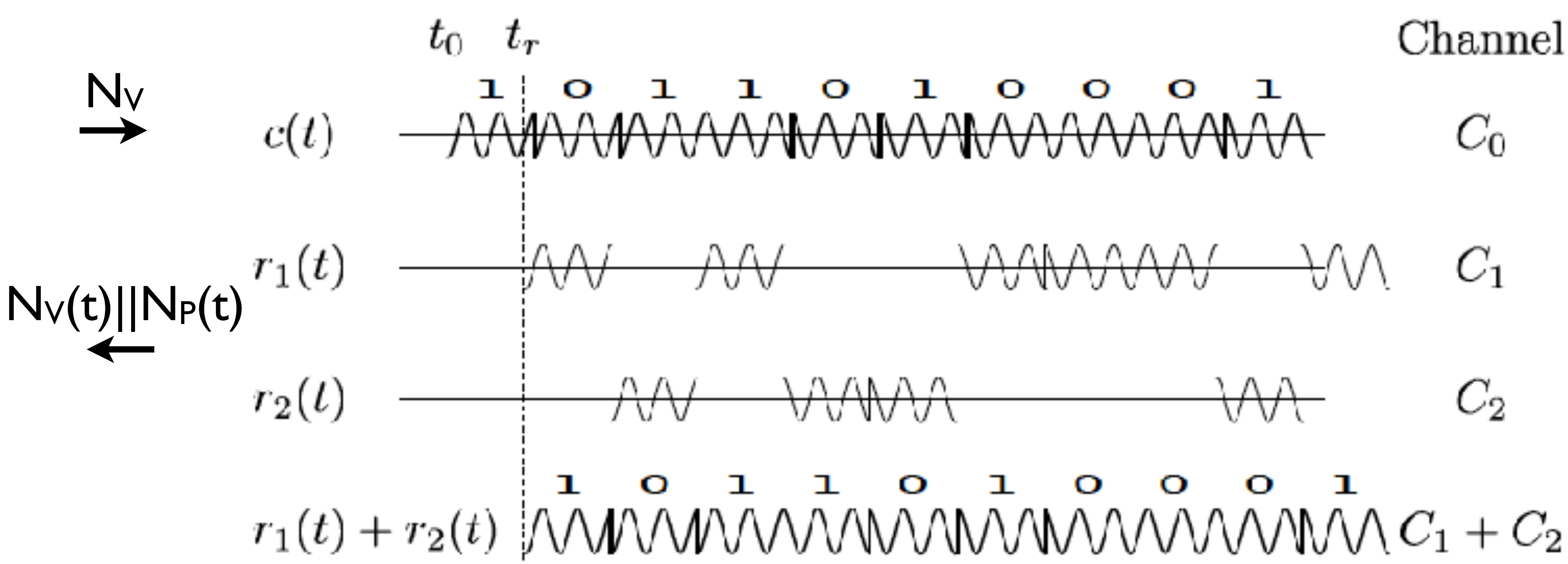
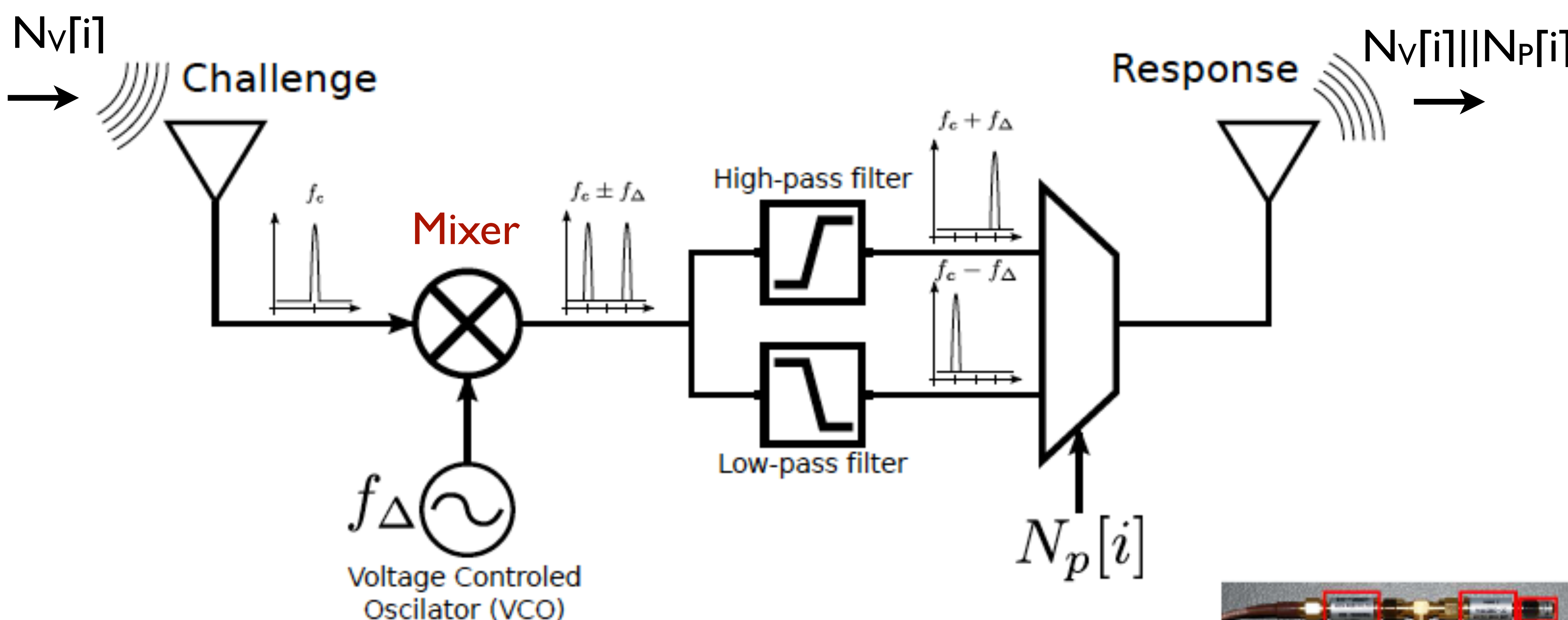
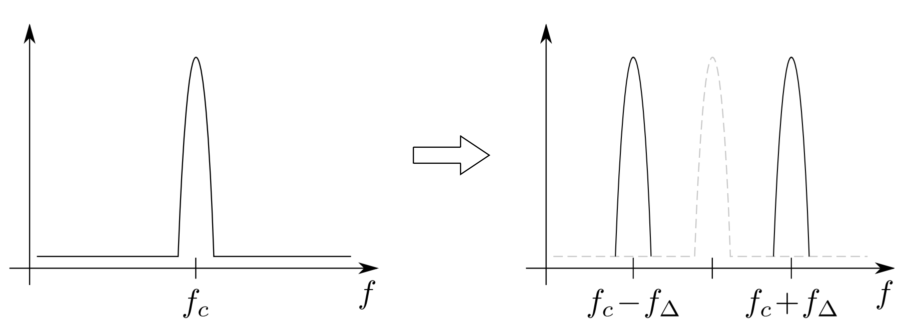
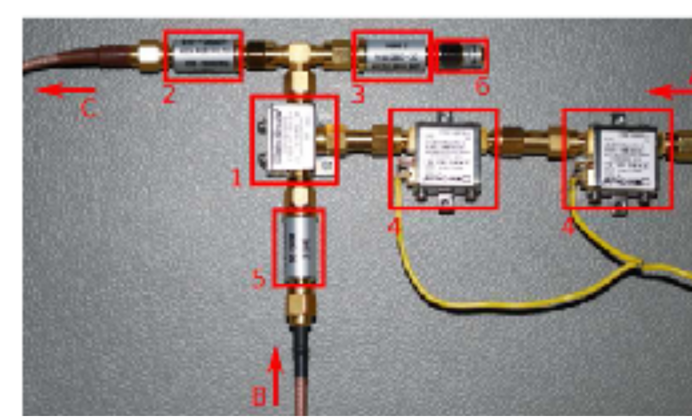


# A new Function: CRCS

## Implementation of CRCS



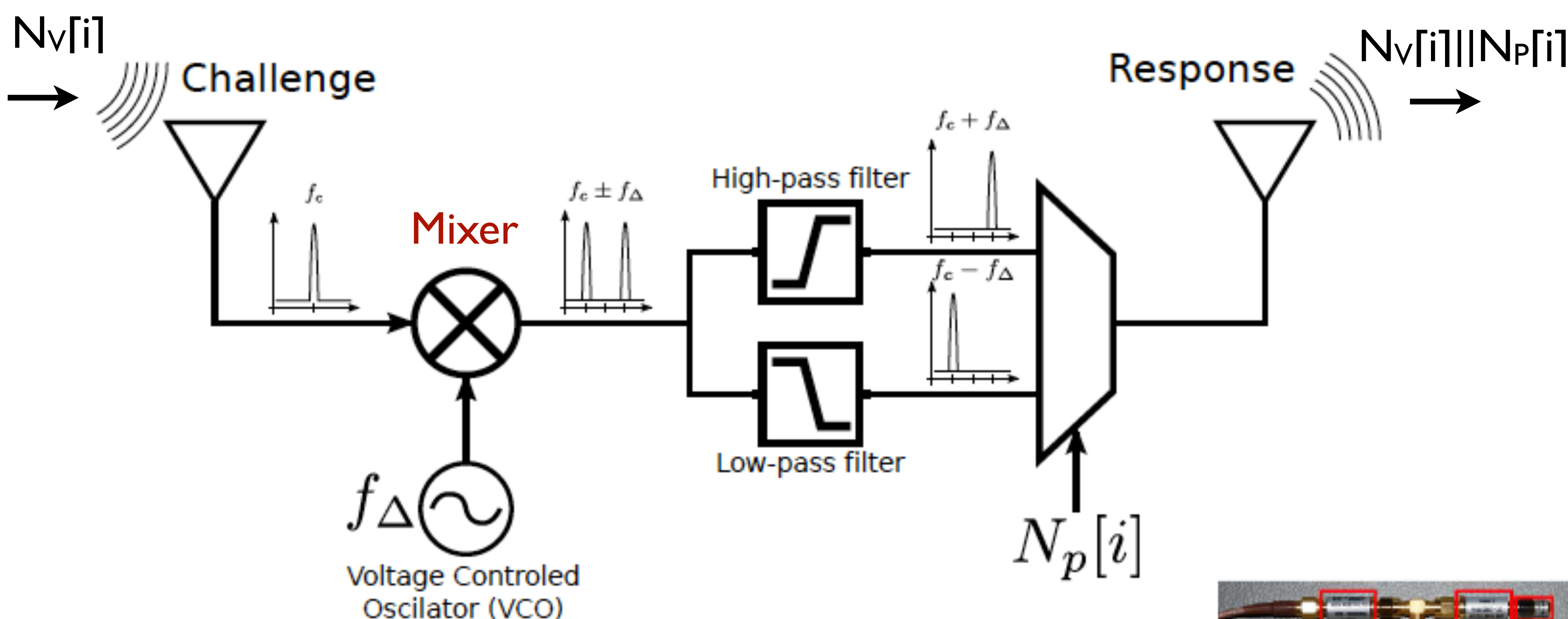



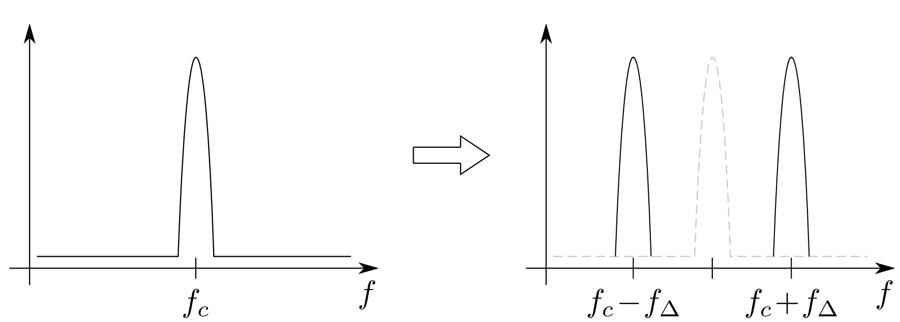
Mixer up+down converts the input signal

# A new Function: CRCS

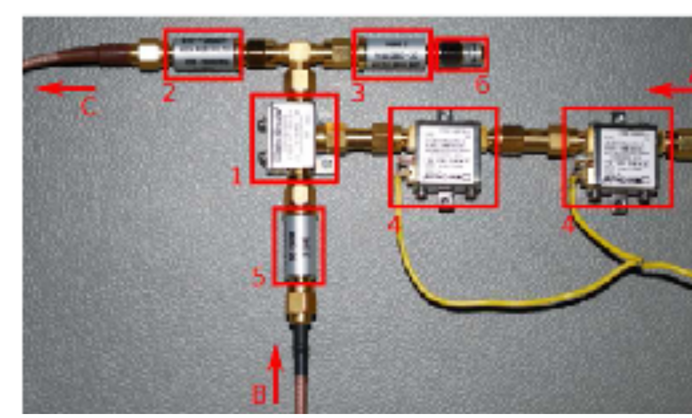
## Implementation of CRCS

$t_p$ < 1ns, st. dev. 61ps, full duplex




Mixer up+down converts the input signal



# A new Function: CRCS

CRCS++ (measured at the input/output of the prover)

# Two basic Attacks on DB protocols

*Distance Fraud*

- dishonest prover pretends to be closer to the verifier
- "pacemaker scenario"

Distance Fraud


*Mafia Fraud*

- honest prover
- attacker convinces verifier and prover that they are closer
- relay attack ("car and key scenario)

Mafia Fraud

# A new Function: CRCS

CRCS-based DB protocol *(vs Distance and Mafia Fraud)*

| | $P$ (Prover) | | $V$ (Verifier) |
|---|---|---|---|
| | Pick $N_p$ | | |
| | $c_p \leftarrow commit(N_p, P)$ | | |
| | | $\xrightarrow{c_p}$ | |
| | | | Pick $N_v$ |
| *fast phase* | $r \leftarrow CRCS(N_v, N_p)$ | $N_v$, $r$ | Record $\Delta t$ |
| | $n \leftarrow delay()$ | | $N'_p \leftarrow channel(r)$ |
| | | | $N'_v \leftarrow signal(r)$ |
| | | | $n' \leftarrow delay(r)$ |
| | | $\xrightarrow{sign(c_p,n,V,N_p,N_v)}$ | |
| | | | Verify $\{\Delta t,\ n = n',$ |
| | | | $N'_v = N_v,\ N'_p = N_p,$ |
| | | | $sign(c_p, n, V, N_p, N_v)\}$ |

# A new Function: CRCS

CRCS-based DB protocol *(vs Distance and Mafia Fraud)*

| | $P$ (Prover) | | $V$ (Verifier) |
|---|---|---|---|
| | Pick $N_p$ | | |
| | $c_p \leftarrow commit(N_p, P)$ | | |
| | | $\xrightarrow{c_p}$ | |
| | | | Pick $N_v$ |
| *fast phase* | $r \leftarrow CRCS(N_v, N_p)$ | $\xleftarrow{N_v}$ $\xrightarrow[r]{}$ | Record $\Delta t$ → *distance* |
| | $n \leftarrow delay()$ | | $N'_p \leftarrow channel(r)$ |
| | | | $N'_v \leftarrow signal(r)$ |
| | | | $n' \leftarrow delay(r)$ |
| | | $\xrightarrow{sign(c_p, n, V, N_p, N_v)}$ | |
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CRCS-based DB protocol *(vs Distance and Mafia Fraud)*

| | $P$ (Prover) | | $V$ (Verifier) | |
|---|---|---|---|---|
| | Pick $N_p$ | | | |
| | $c_p \leftarrow commit(N_p, P)$ | | | |
| | | $\xrightarrow{c_p}$ | | |
| | | | Pick $N_v$ | |
| *fast phase* | $r \leftarrow CRCS(N_v, N_p)$ | $N_v$ / $\xrightarrow[r]{}$ | Record $\Delta t$ | → *distance* |
| | $n \leftarrow delay()$ | | $N_p' \leftarrow channel(r)$ | |
| *slow phase interpretation of $N_v$* | | | $N_v' \leftarrow signal(r)$ | |
| | | | $n' \leftarrow delay(r)$ | |
| | | $\xrightarrow{sign(c_p, n, V, N_p, N_v)}$ | | |
| | | | Verify $\{\Delta t,\ n = n',$ $N_v' = N_v,\ N_p' = N_p,$ $sign(c_p, n, V, N_p, N_v)\}$ | |

# A new Function: CRCS

## CRCS-based DB protocol *(vs Distance and Mafia Fraud)*

| | $P$ (Prover) | | $V$ (Verifier) | |
|---|---|---|---|---|
| | Pick $N_p$ | | | |
| | $c_p \leftarrow commit(N_p, P)$ | | | |
| | *DH and MF protection* | $\xrightarrow{c_p}$ | | |
| | | | Pick $N_v$ | |
| *fast phase* | $r \leftarrow CRCS(N_v, N_p)$ | $N_v$ / $\xrightarrow{r}$ | Record $\Delta t$ | → *distance* |
| | $n \leftarrow delay()$ | | $N'_p \leftarrow channel(r)$ | |
| | *slow phase interpretation of* $N_v$ | | $N'_v \leftarrow signal(r)$ | |
| | | | $n' \leftarrow delay(r)$ | |
| | | $\xrightarrow{sign(c_p, n, V, N_p, N_v)}$ | | |
| | | | Verify $\{\Delta t,\ n = n',$ | |
| | | | $N'_v = N_v,\ N'_p = N_p,$ | |
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# A new Function: CRCS

CRCS-based DB protocol *(vs Distance and Mafia Fraud)*

| $P$ (Prover) | | $V$ (Verifier) |
|---|---|---|
| Pick $N_p$ | | |
| $c_p \leftarrow commit(N_p, P)$ | | |
| *DH and MF protection* | $\xrightarrow{c_p}$ | |
| | *DF protection* | Pick $N_v$ |
| *fast phase* $r \leftarrow CRCS(N_v, N_p)$ | $\xleftarrow{N_v}$ $\xrightarrow[r]{}$ | Record $\Delta t$ → *distance* |
| $n \leftarrow delay()$ | | $N'_p \leftarrow channel(r)$ |
| | | $N'_v \leftarrow signal(r)$ |
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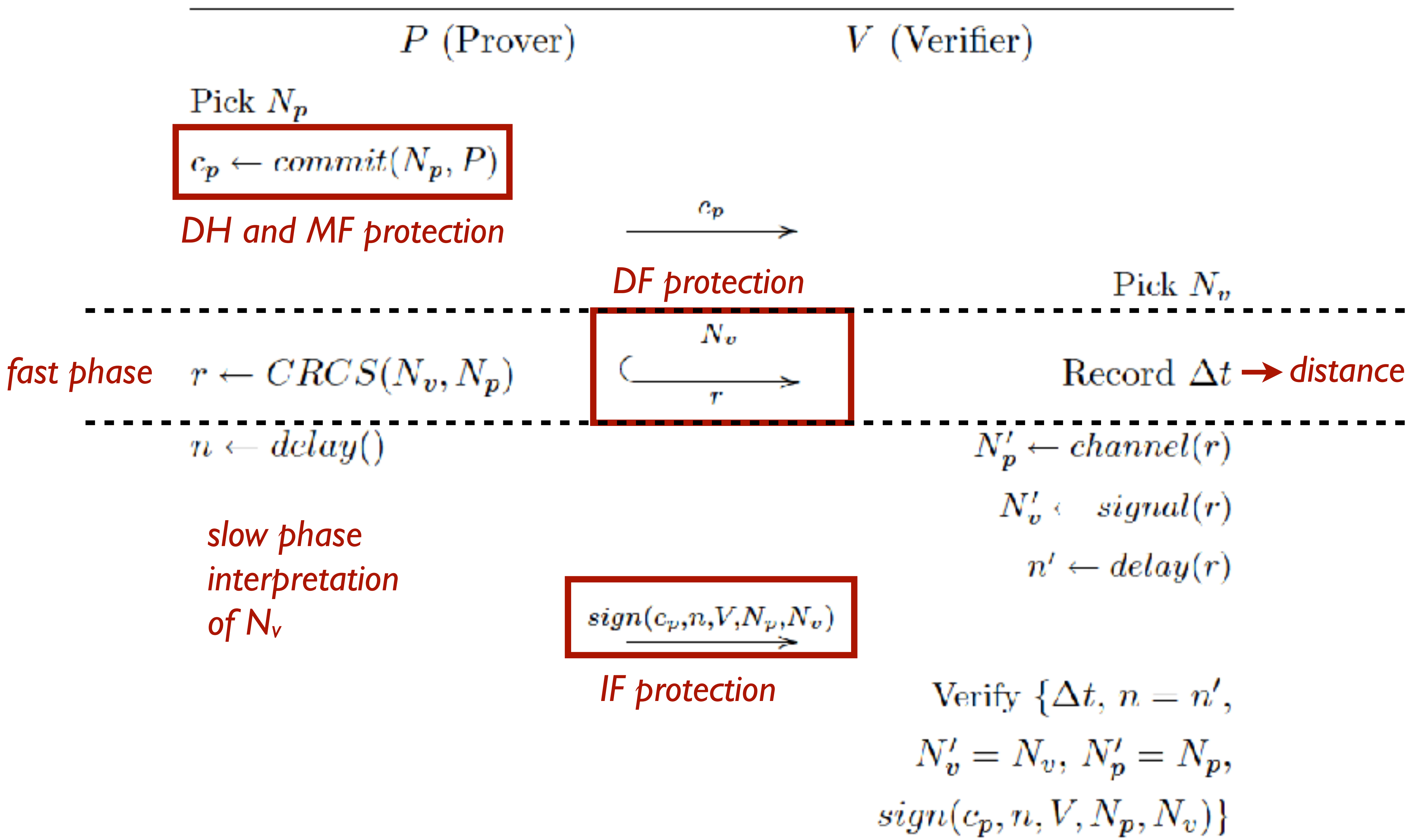
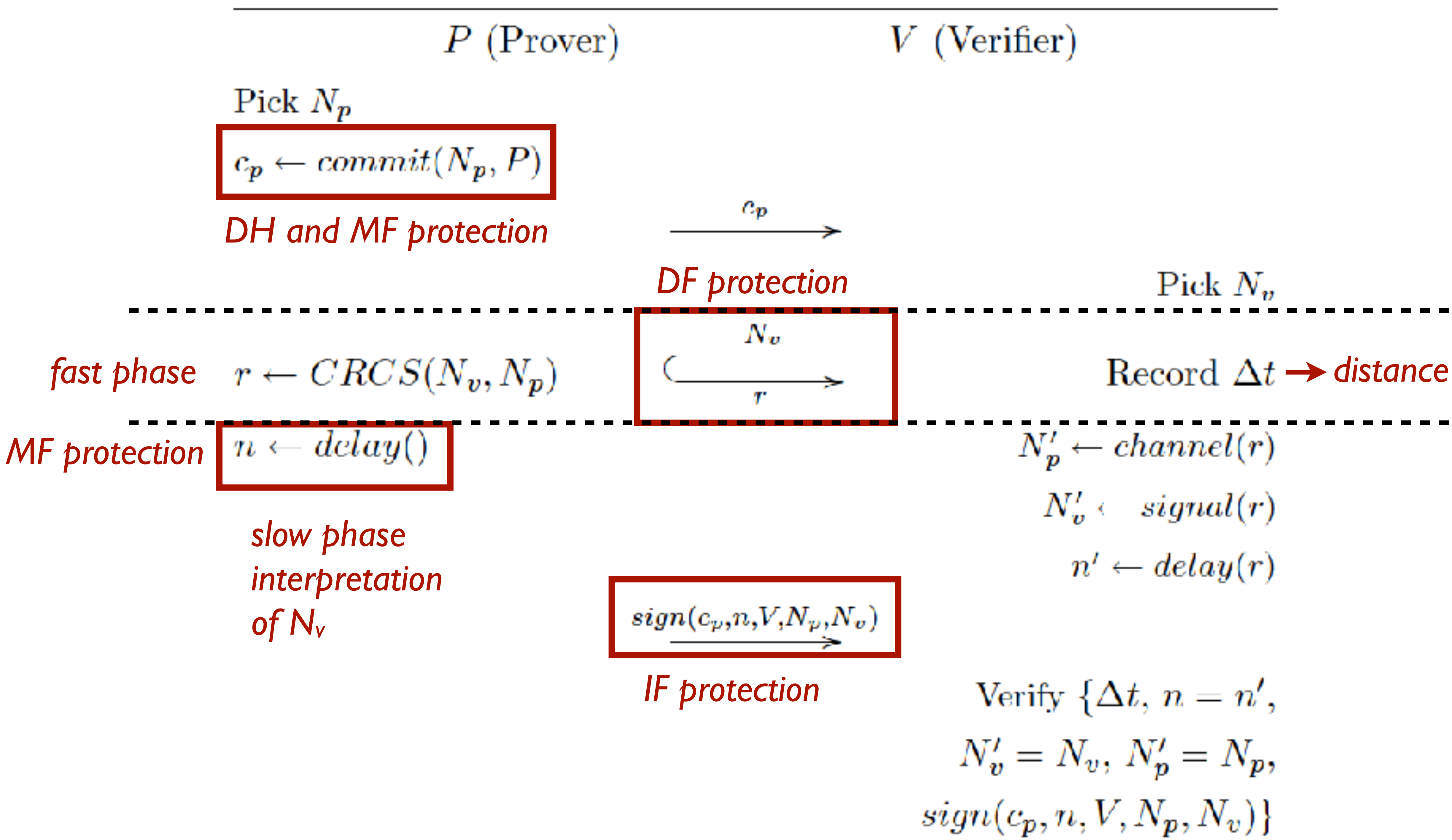
# A new Function: CRCS

CRCS-based DB protocol *(vs Distance and Mafia Fraud)*



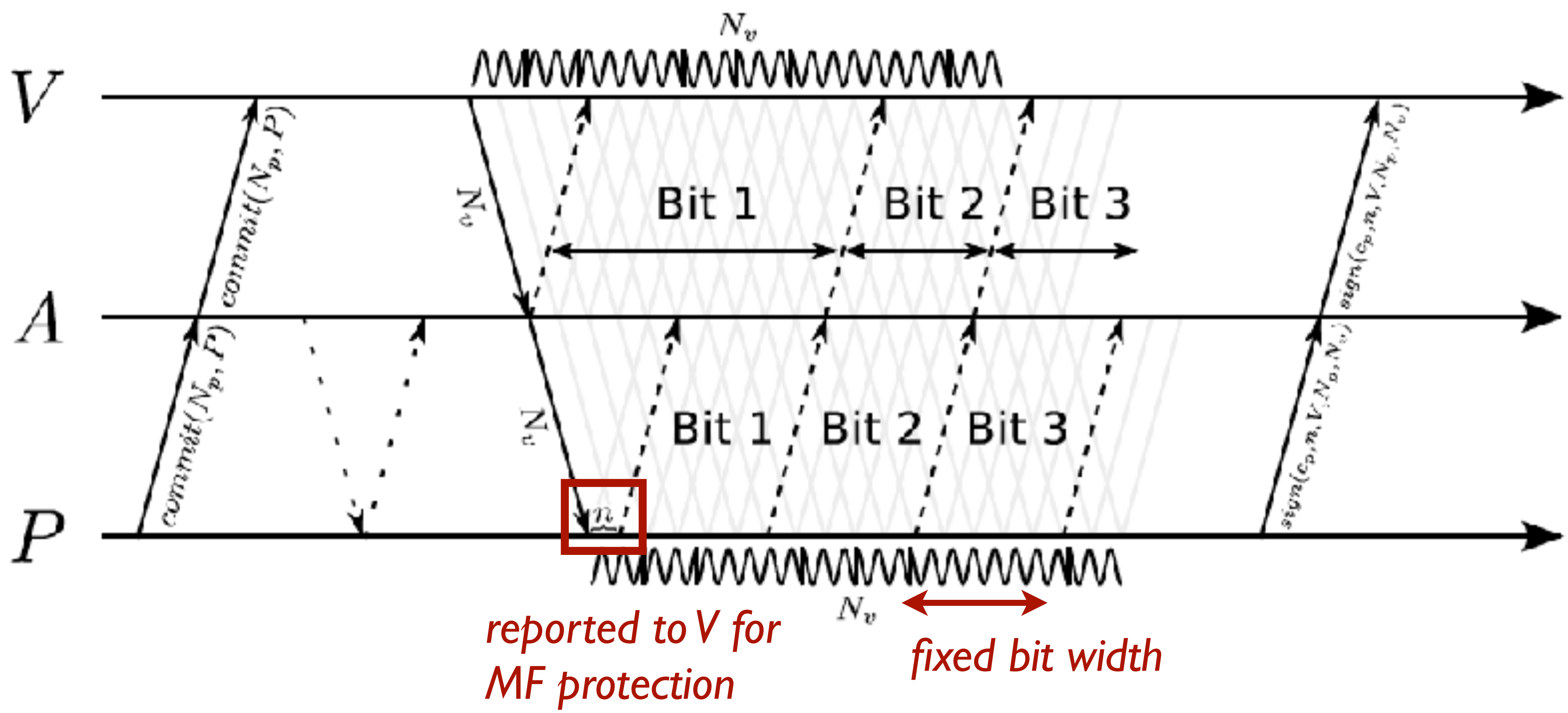
# A new Function: CRCS

## CRCS-based DB protocol *(vs Distance and Mafia Fraud)*



# A new Function: CRCS

Mafia Fraud Detection *(physical layer)*




MF attack: $\frac{1}{2^{|N_p|}}$ ; DF attack: $\frac{1}{2^{|N_v|}}$

*CRCS eliminates* early detection, late commit attacks

# Ongoing work on CRCS

Using CRCS the prover also reflects noise
=> CRCS increases complexity of the Verifier

In essence, CRCS trades

- robustness for increased security
- reduces complexity of the prover but increases the complexity of the verifier
- range might be affected by the use of CRCS (?)

What I didn't talk about (synchronization, preambles, ...).

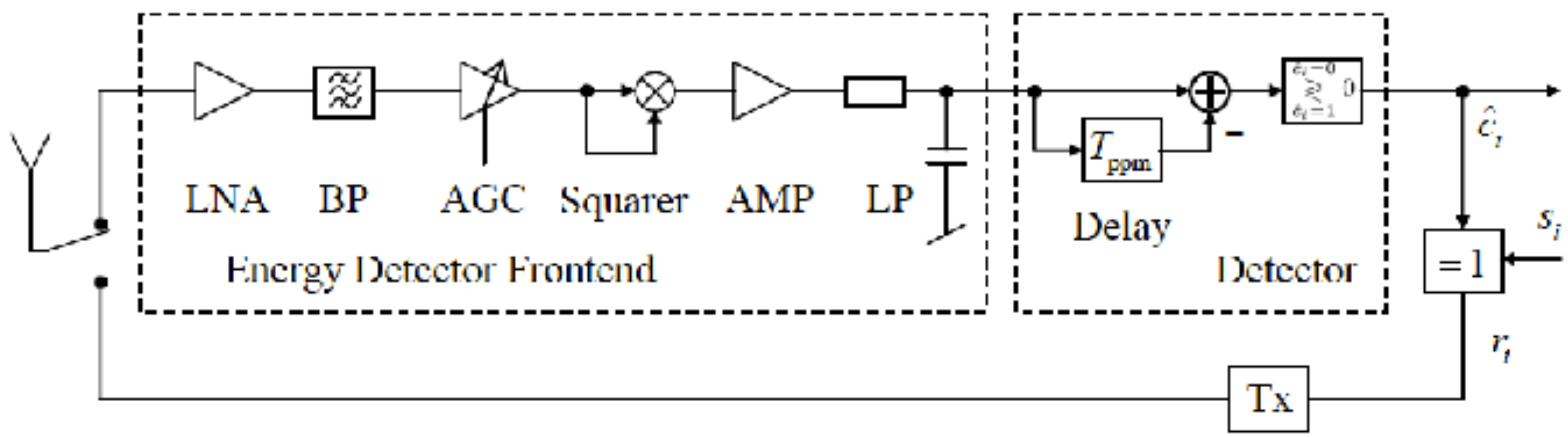
Ongoing implementations ...

...

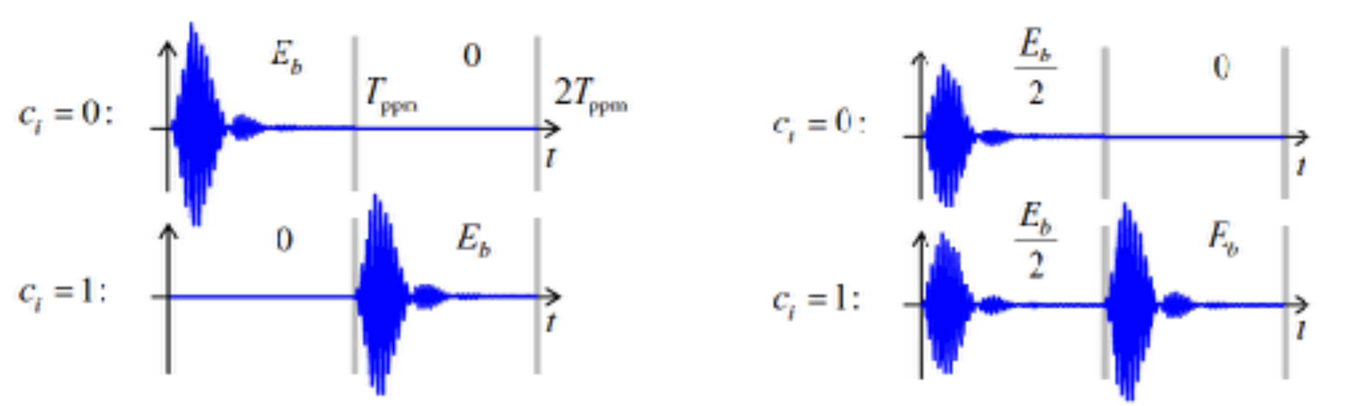
# Other Implementation Efforts

Going back to XOR.

- What is the "fastest" implementation that we can make with f(Nv,Np) = Nv⊕Np?
- What kind of a receiver are we considering?




- A different modulation (SEM vs BPPM)



# Protocol Analysis

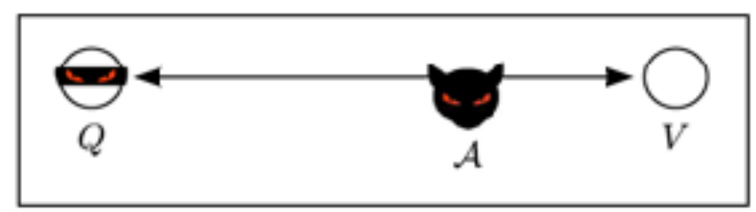
Two main protocol constructs:

- Hancke-Kuhn
- Brands-Chaum

Three main attacks considered:

Distance Fraud


Terrorist Fraud




Mafia Fraud

# Protocol Analysis

Two main protocol constructs:

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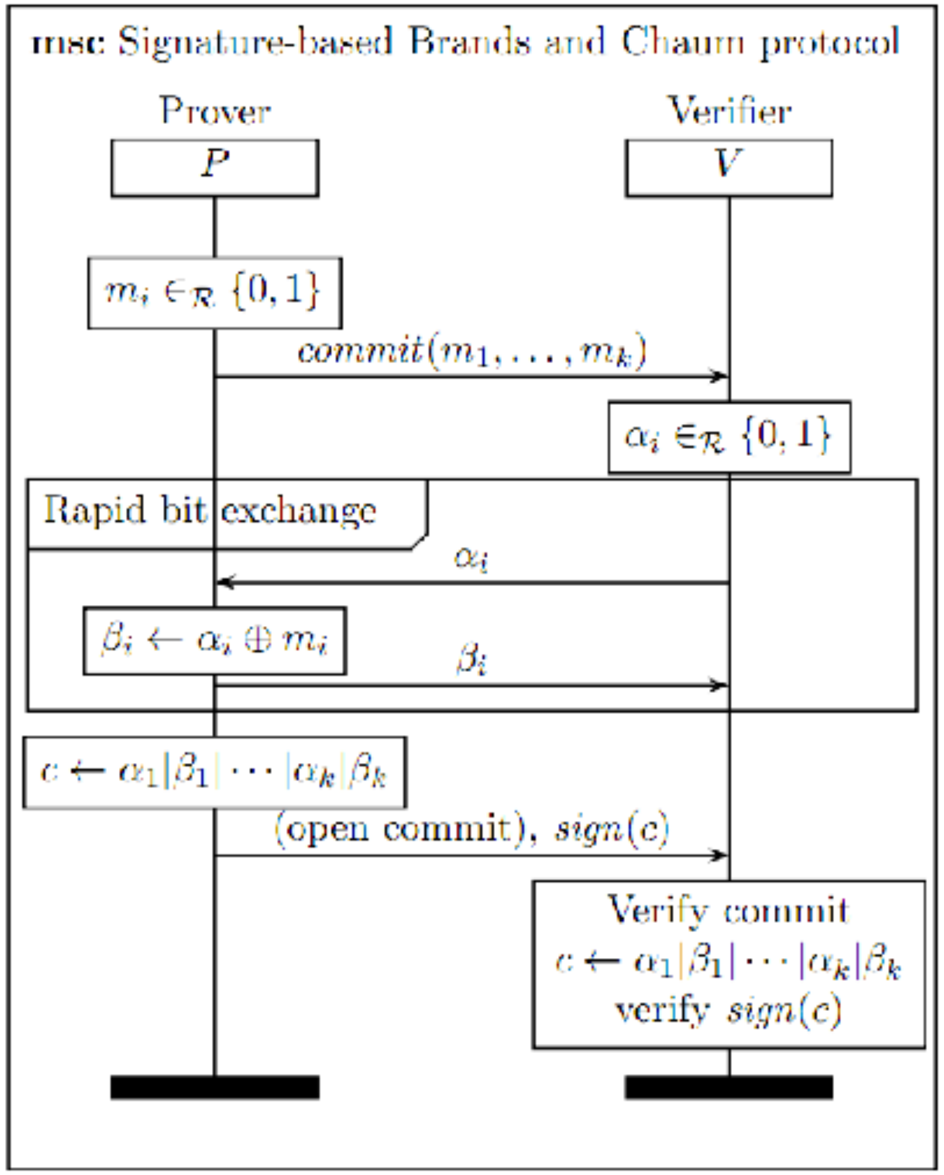
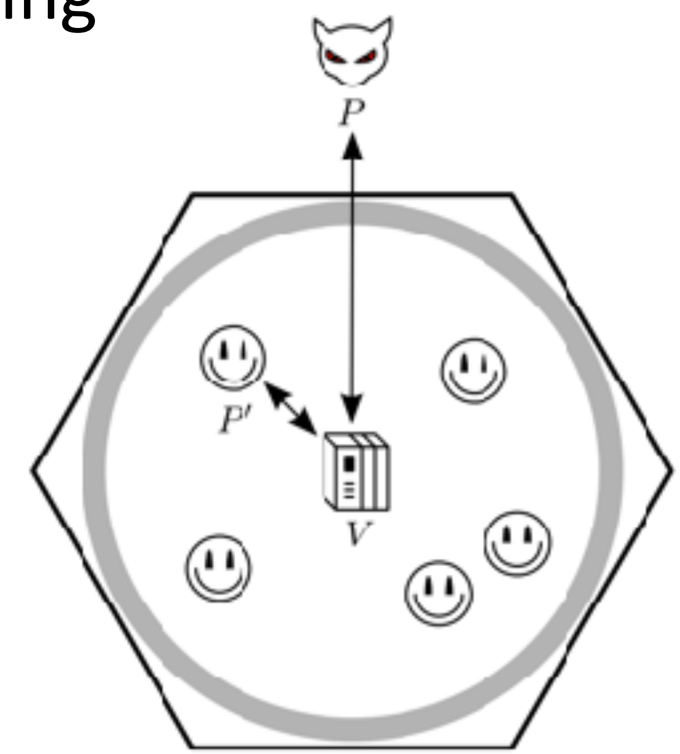
- Brands-Chaum

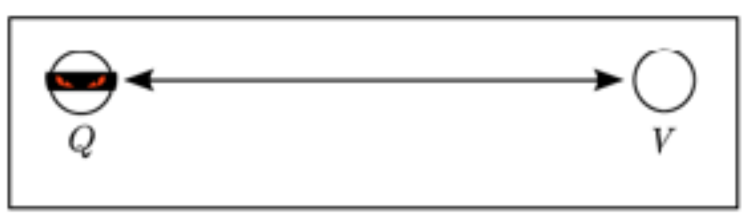


# Protocol Analysis

Novel attack: Distance Hijacking



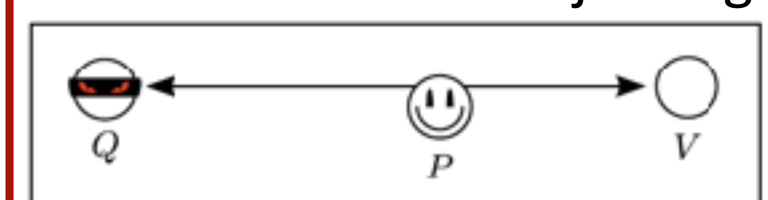

Distance Fraud




Terrorist Fraud

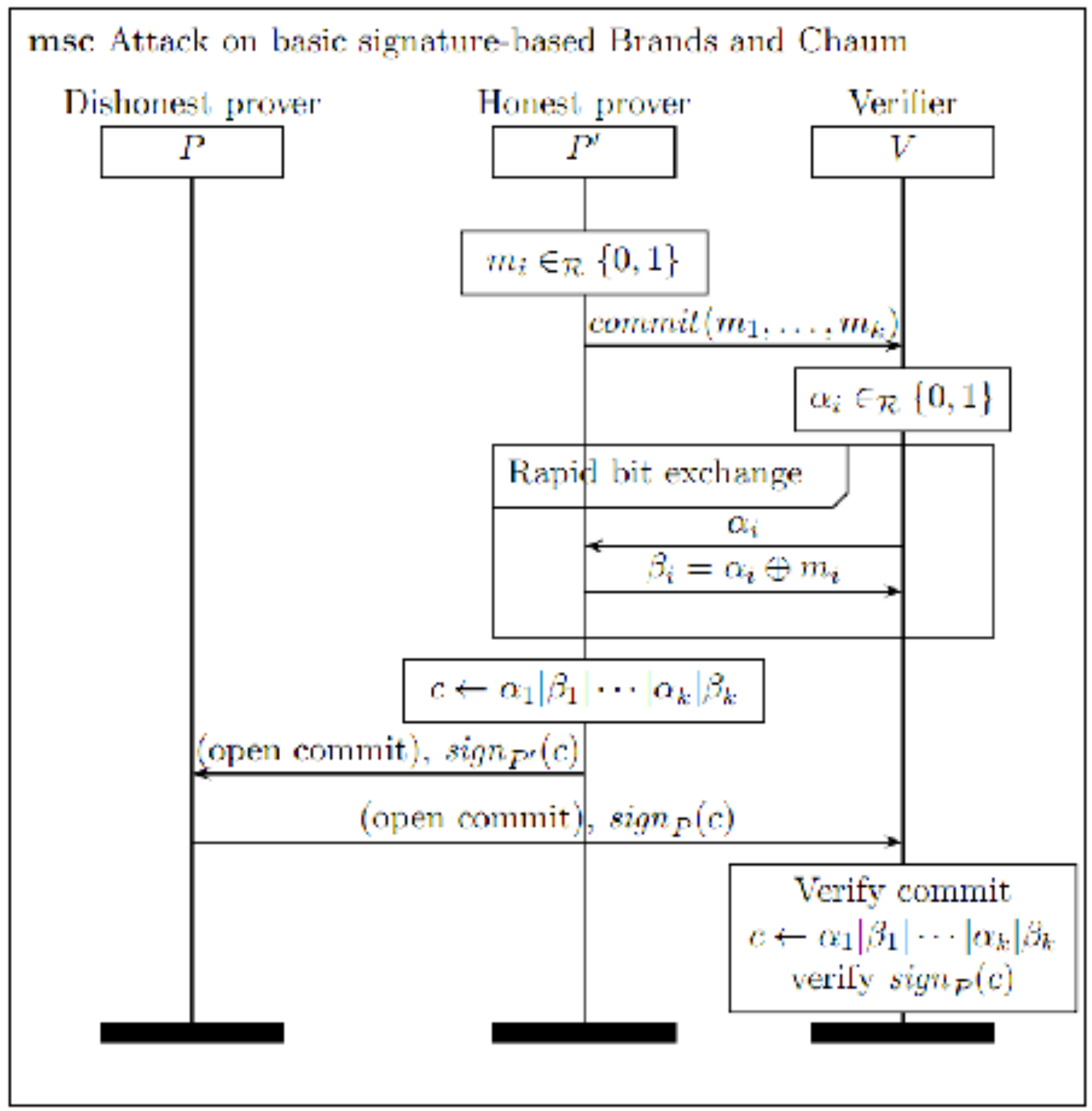

Mafia Fraud


Distance Hijacking



# Protocol Analysis

## Distance Hijacking on Brands and Chaum



# Protocol Analysis

## More Distance Hijacking

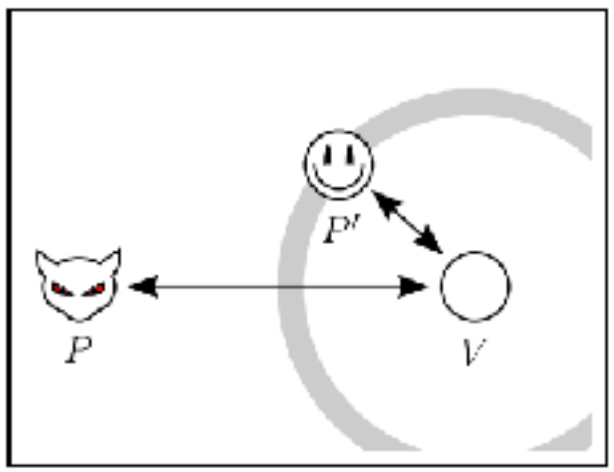



Figure 7: Scenario in which $V$ accepts protocol sessions from multiple provers, here $P$ and $P'$, where Distance Hijacking may be a threat.

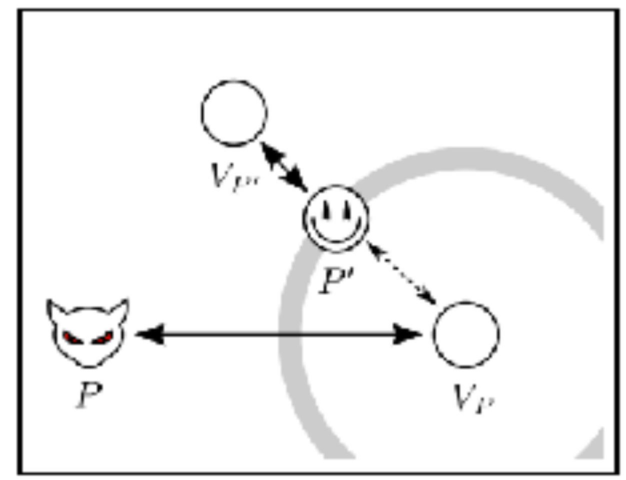
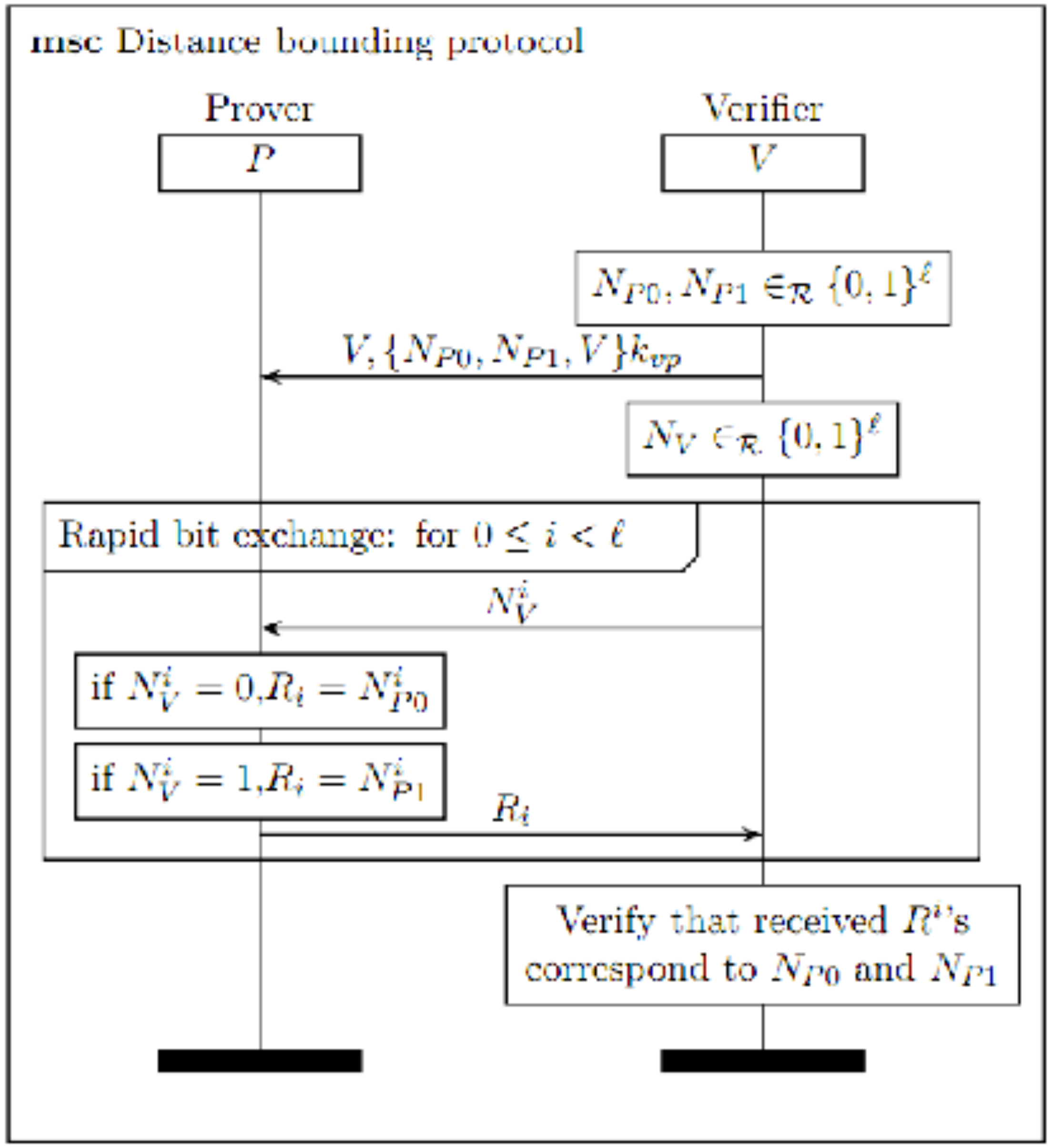



Figure 8: Scenario with multiple prover/verifier pairs, where $V_x$ only accepts sessions from $x$. Even in this case, Distance Hijacking may be possible.

# Protocol Analysis

Attack on Hancke-Kuhn (indirect)



# DB Protocol Analysis (Formal)

Authentication and Key Establishment protocols

- analyzed in the Dolev-Yao model
- no notions of location, channel characteristics, (or time)
- the same frameworks cannot analyze DB protocol

Some new framework can capture physical properties *(time, location, physical layer) e.g., [Basin10]*

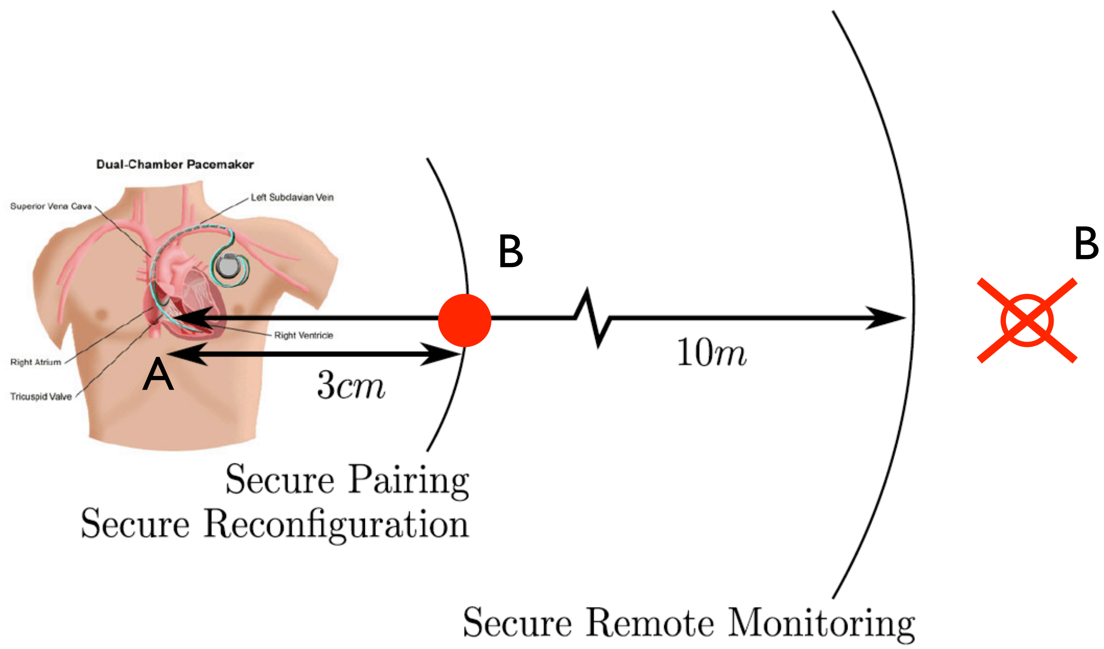
- Model based on experiments with real systems
- Enables formal analysis of DB protocols
- Captured new attacks on DB that we missed in the informal analysis

Other frameworks: Avoine, Meadows,

Game is not over ... (ref. Distance Hijacking attacks)

# One Use of DB -> Authentication Based on *Absence* Awareness

How would Proximity-Based Access Control be implemented?




1. A verifies proximity of B
2. A establishes a *shared secret key* with B (e.g., pairing using DH)
3. The key is used to enforce access control

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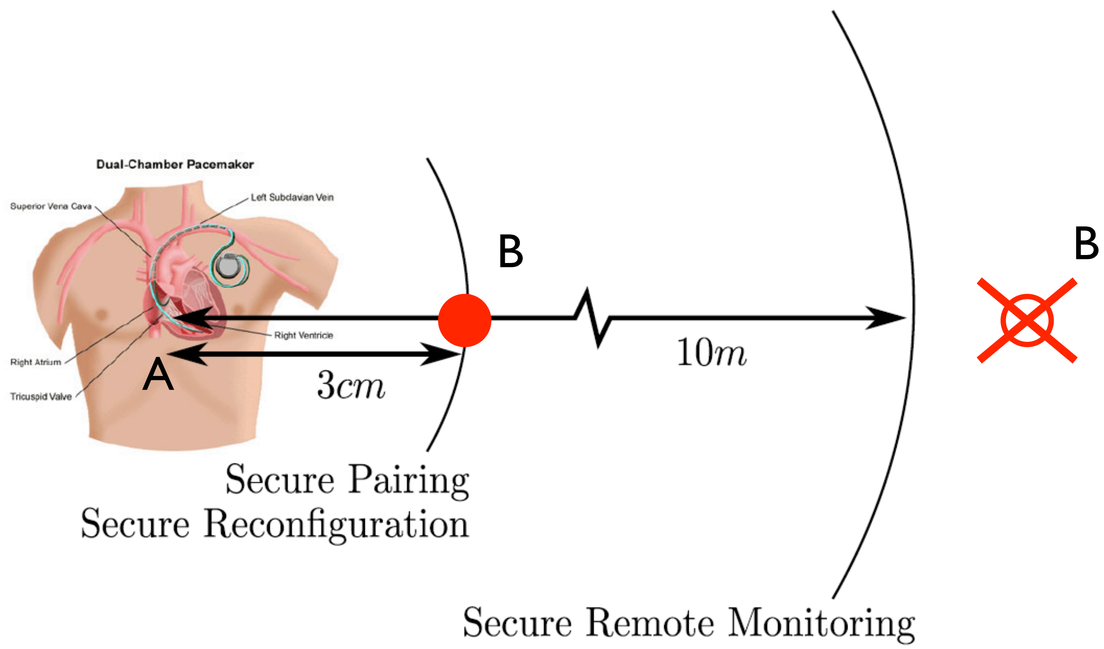


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The protocol needs to ensure that the *key is bound to the distance*.

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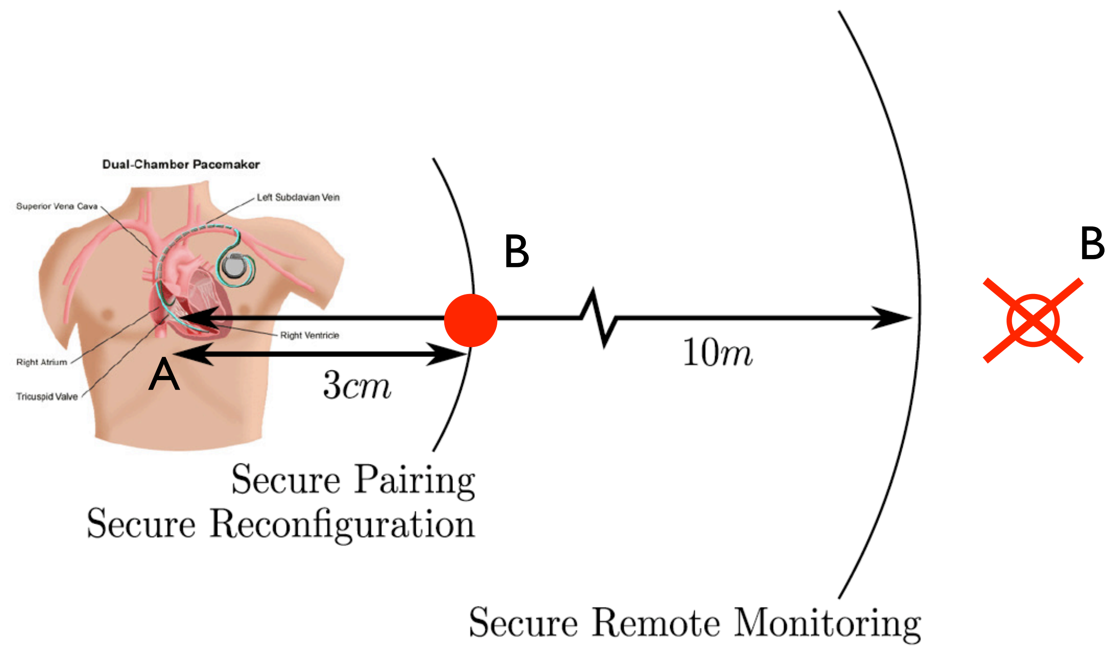


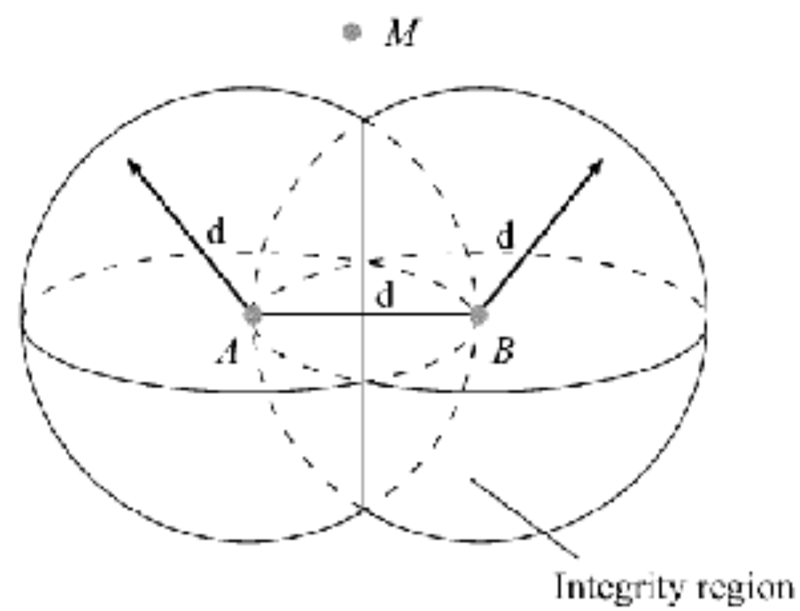


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The protocol needs to ensure that the *key is bound to the distance*.

# Secure Localization

*From Proximity Verification*

*to Location Verification and Secure Localization*

# Secure Localization

*User's perspective:*
to obtain a correct information about its own location

*Infrastructure perspective:*
to obtain a correct information about the location of a device

*Secure localization goals*

- Compute a 'correct' location of a (trusted) device in the presence of an attacker. *(Secure Localization)*
- Verify the correctness of a location of an untrusted device. (that e.g., claims a certain location) *(Location Verification)*

# Secure Localization Schemes

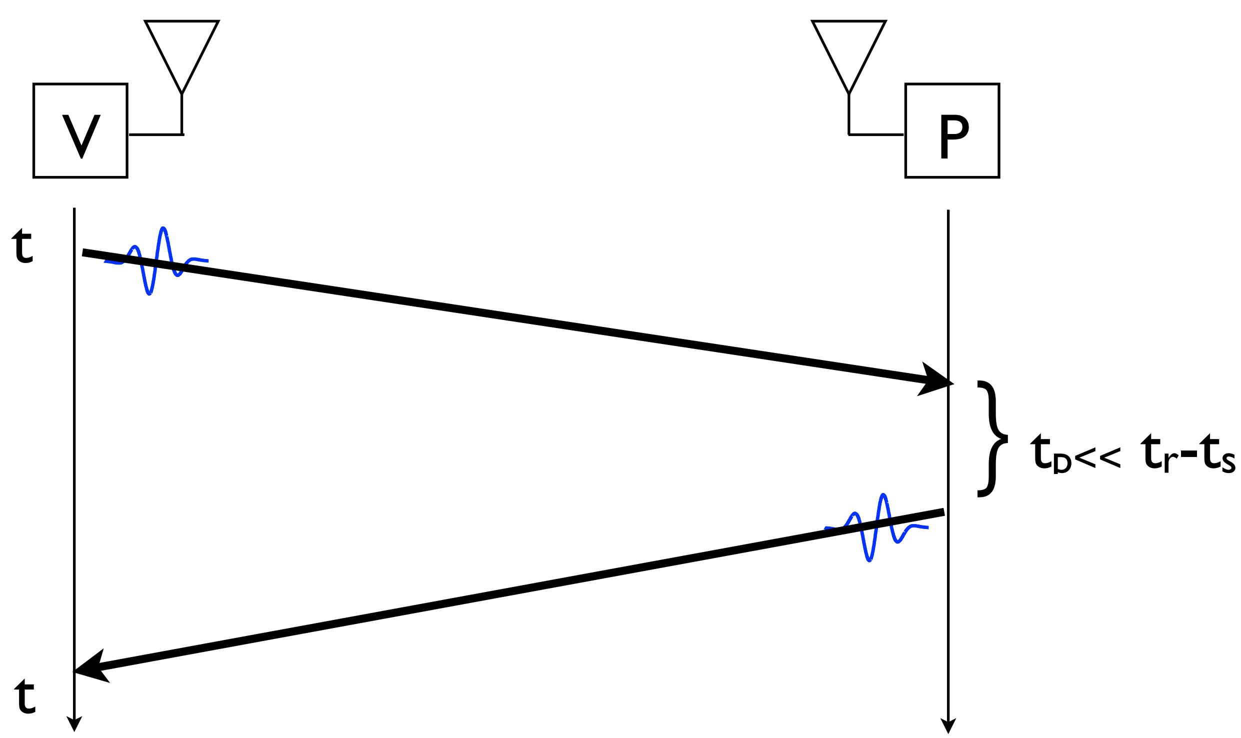
- Verifiable Multilateration
- Location Verification with Hidden and Mobile Stations
- *Secure Broadcast Localization and Time Synchronization (will be covered later in the lectures)*

# Distance Bounding

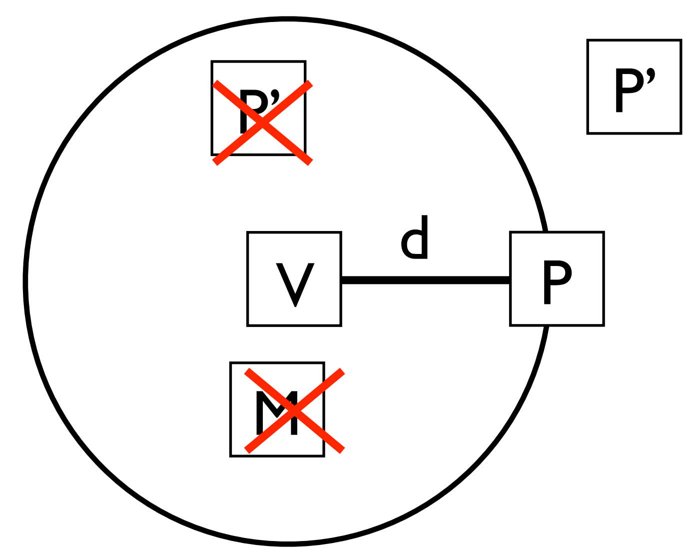
- P can always pretend to be further from V
- M can always convince P and V that they are further away

*=> Distance **enlargement is easy, distance reduction is prevented** using distance bounding protocols*

Ranging




$d = (t_r - t_s - t_P)c/2$



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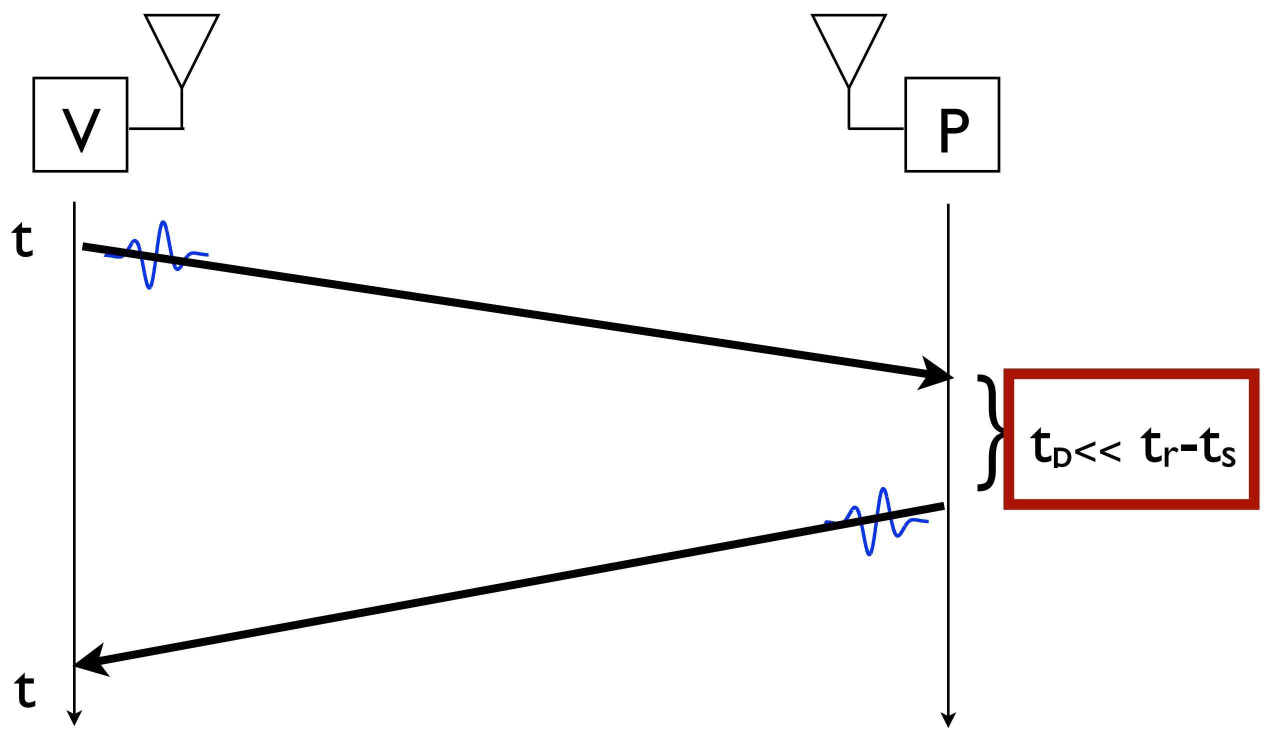


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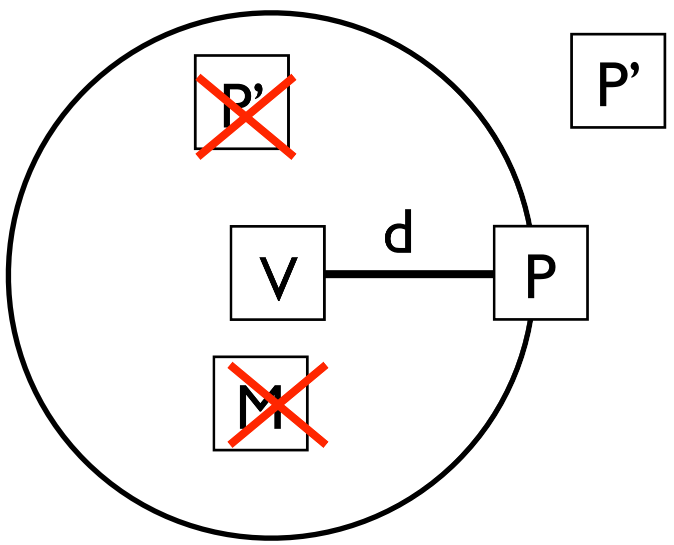

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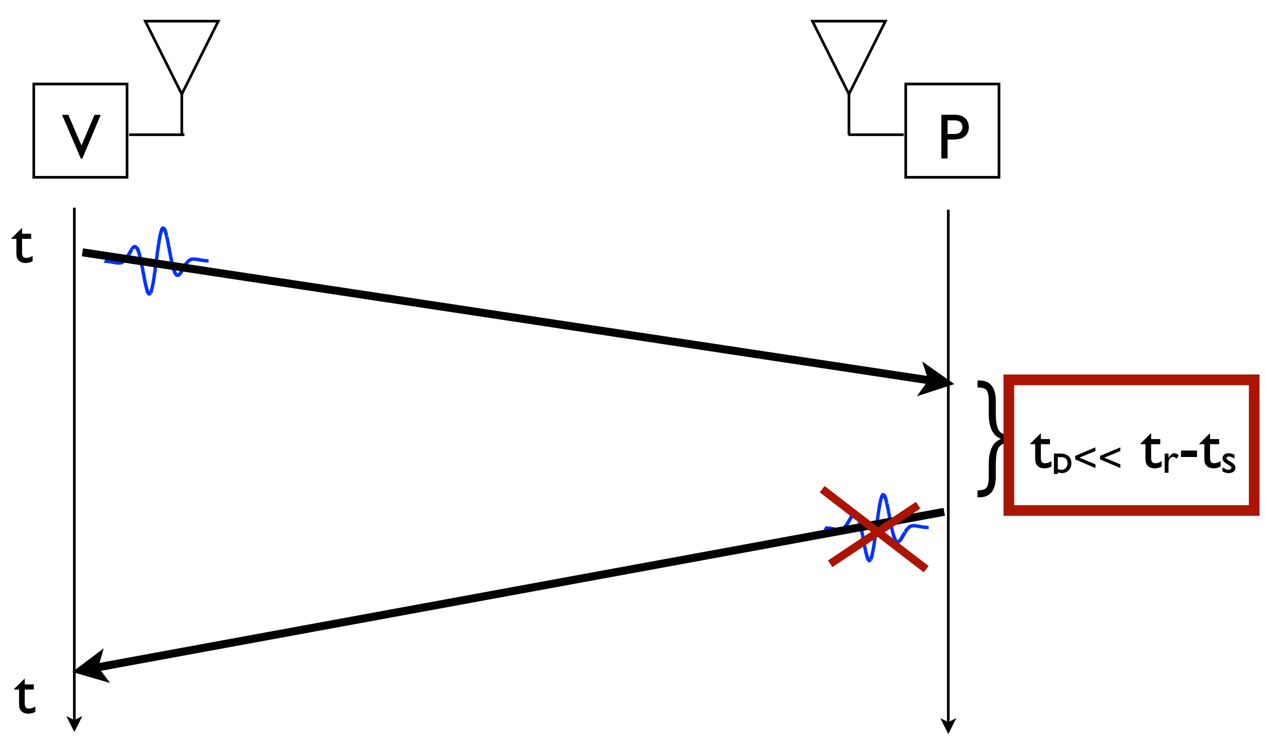


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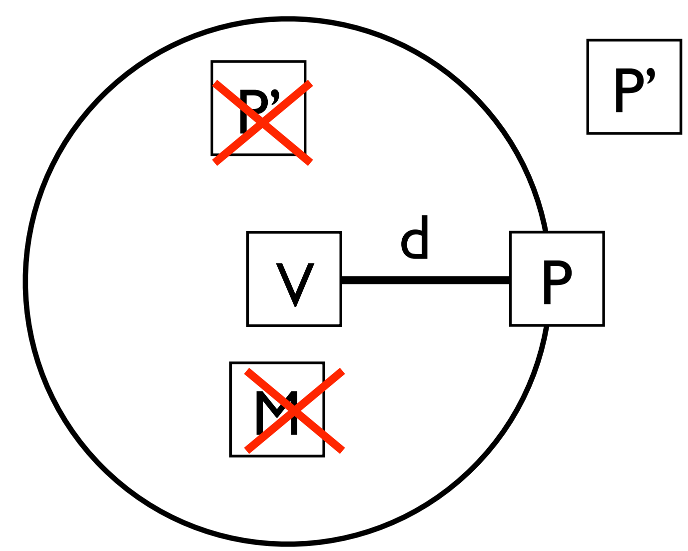

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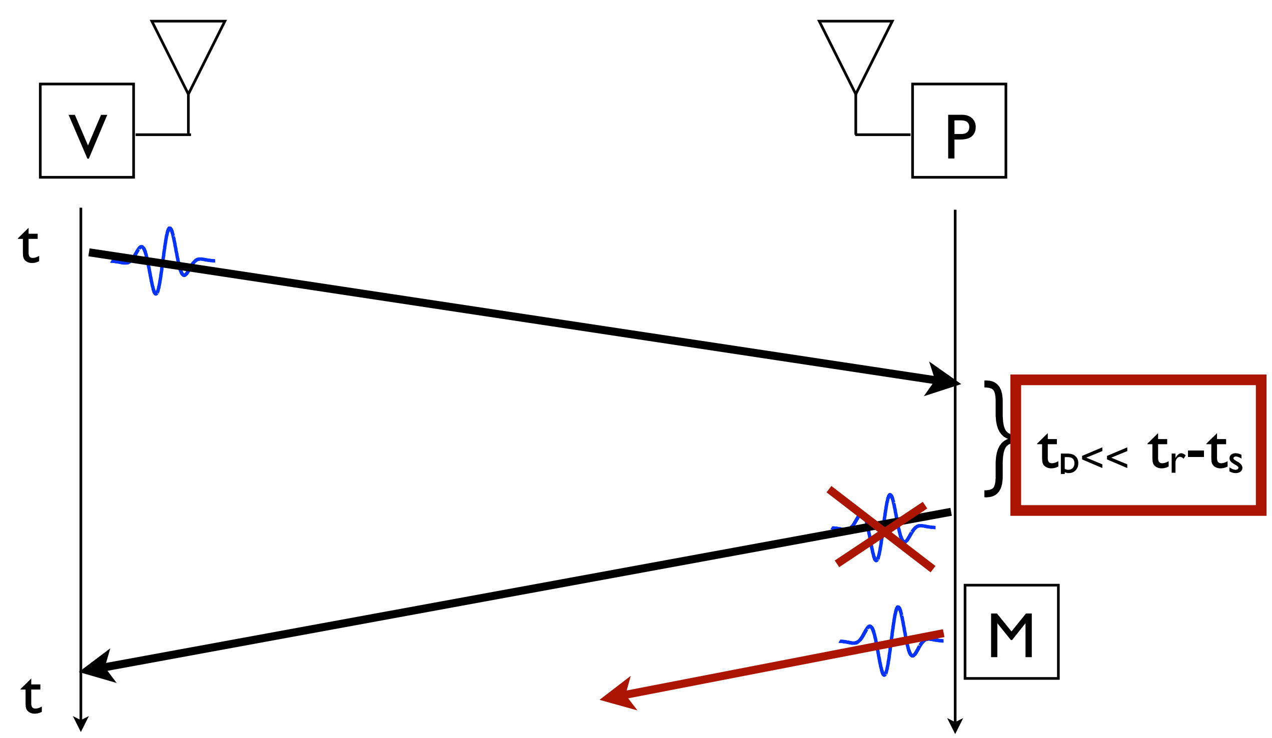


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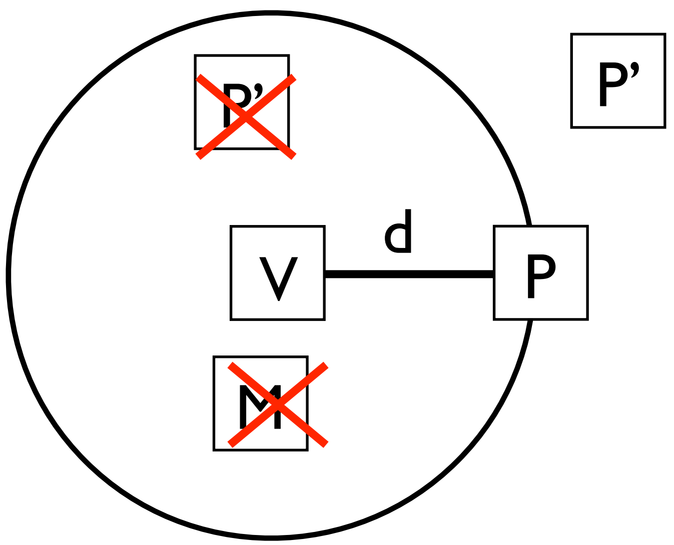
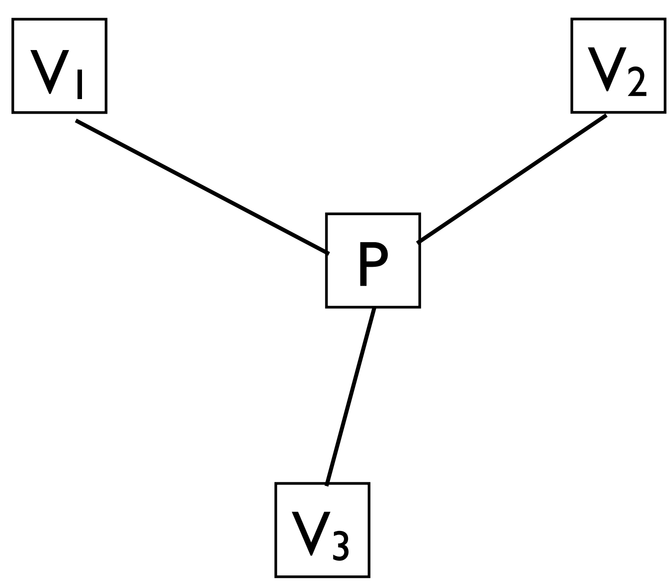


# Verifiable Multilateration

Distance enlargement is easy, distance reduction is prevented using distance bounding protocols

- *So can we realize Location Verification or Secure Localization using Distance Bounding protocols?*



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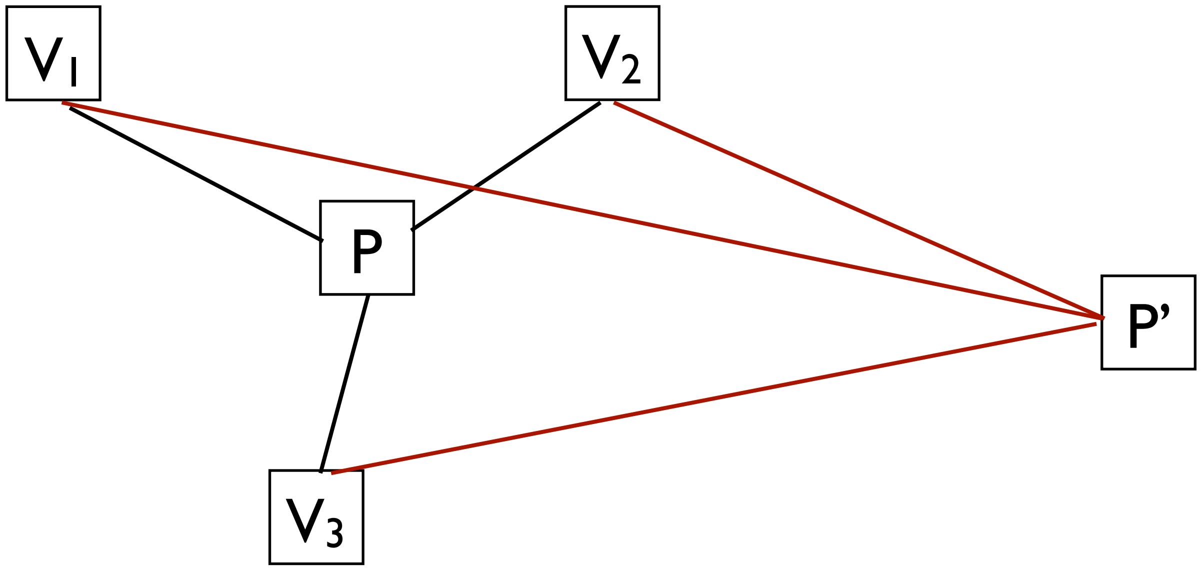
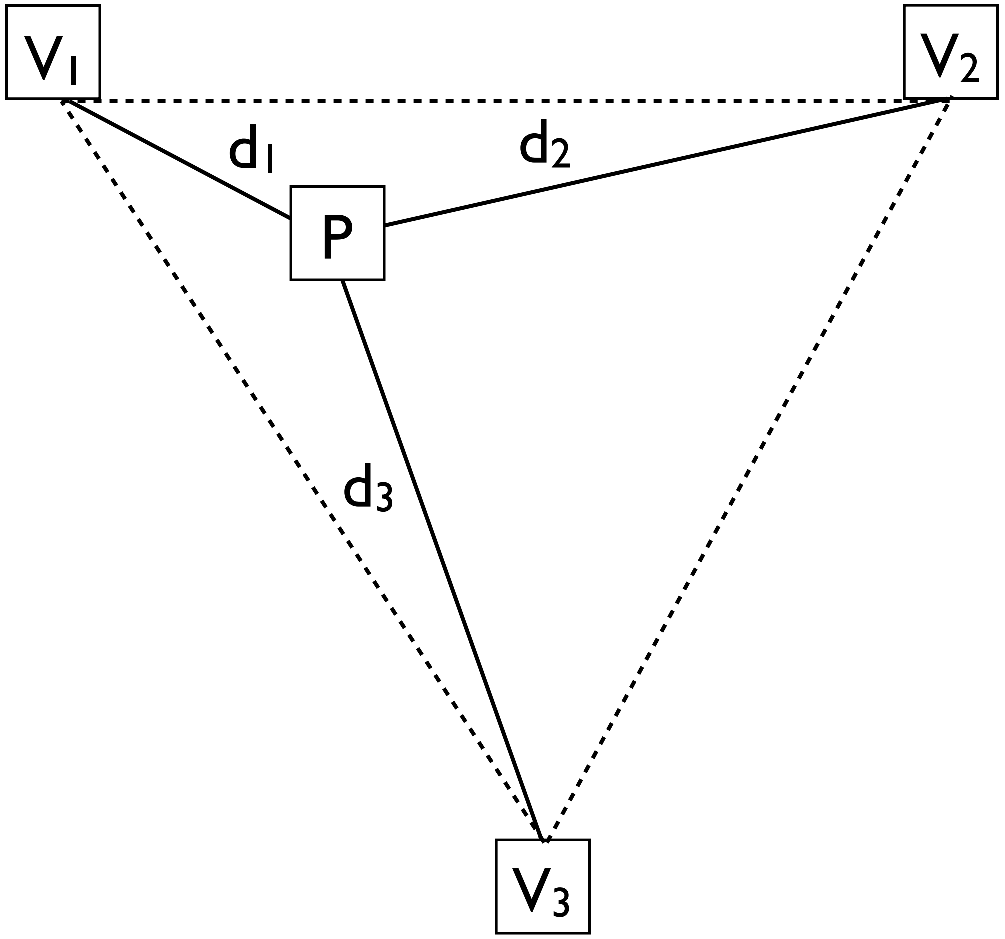


# Verifiable Multilateration

Verifiable Multilateration in 3 steps:

1. Verifiers (known locations) form a *verification triangle*.
2. Based on the measured distance bounds, compute the location of the Prover.
3. *If the computed location is in the verification triangle, the verifiers conclude that this is a correct location.*



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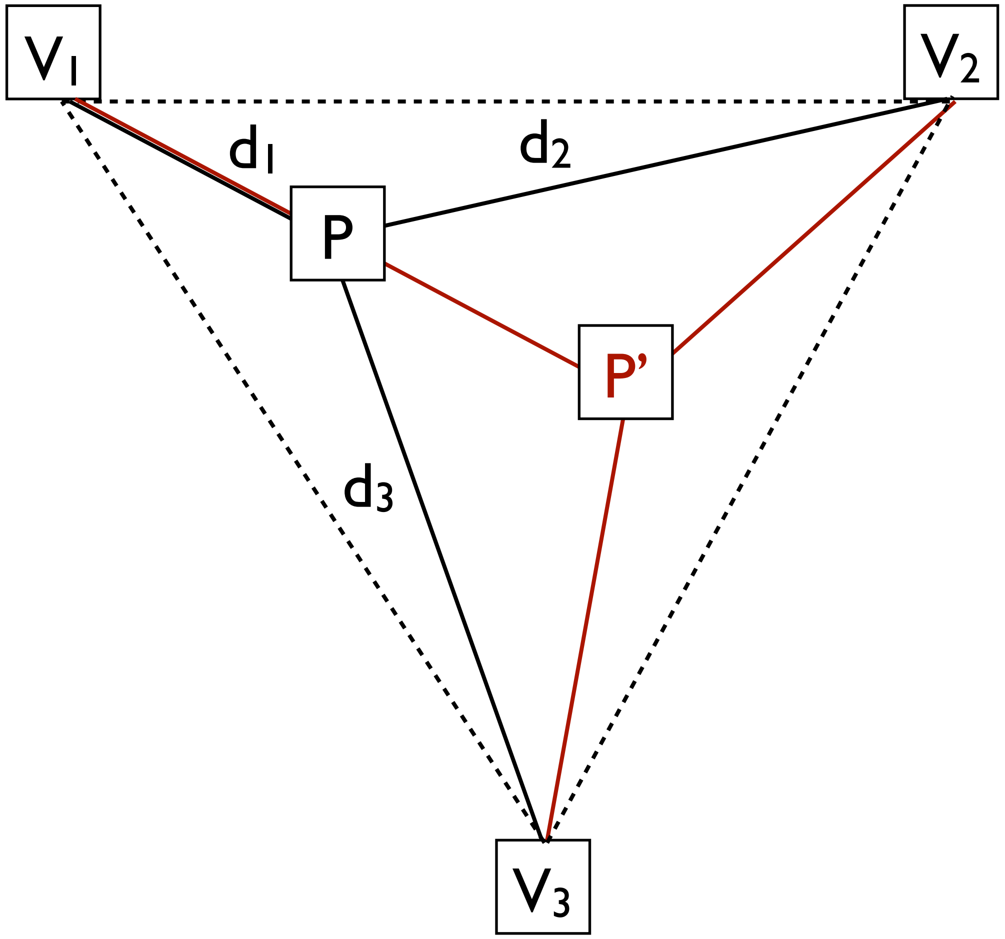

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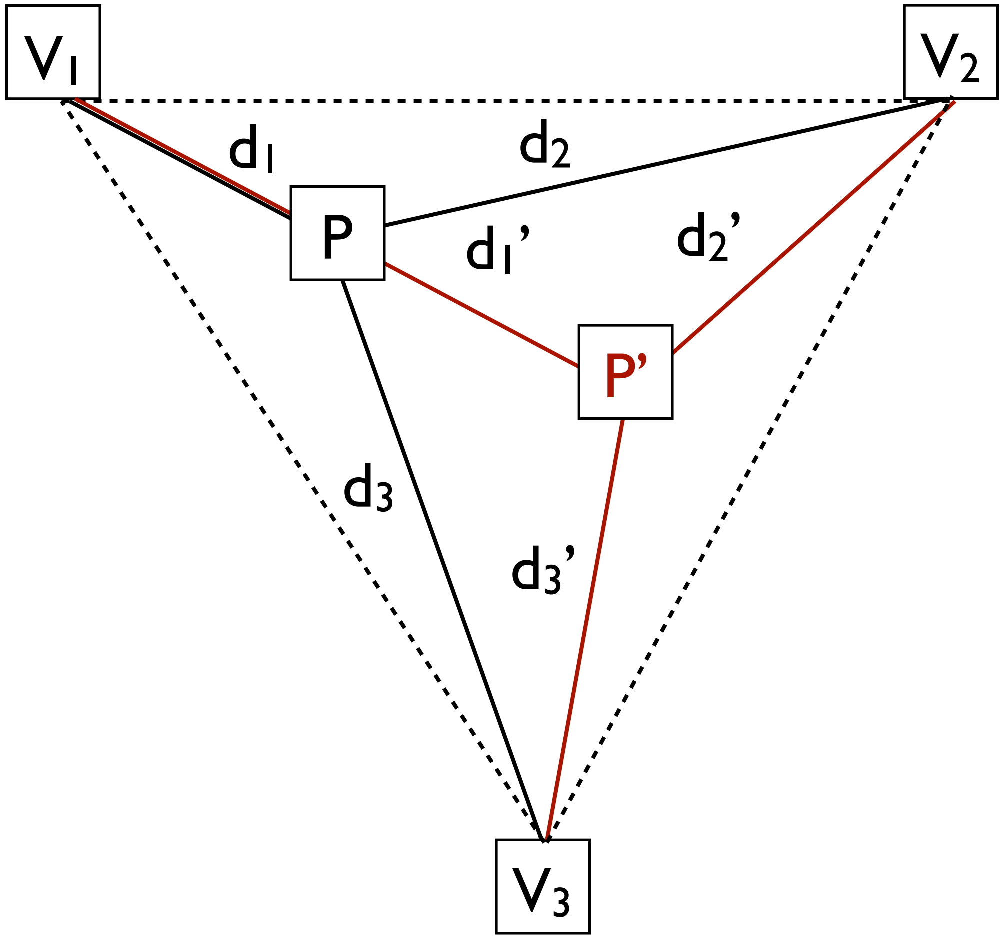
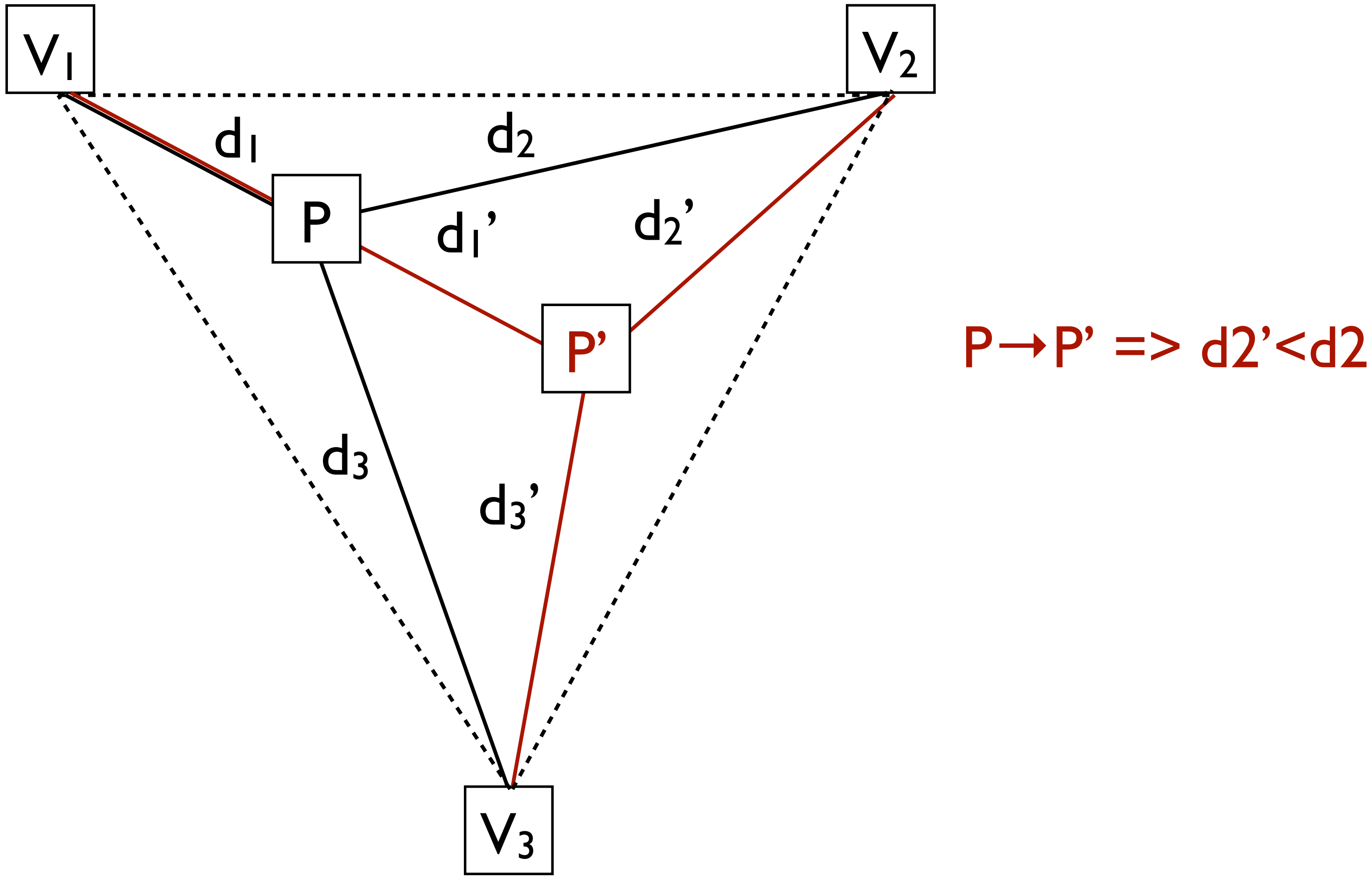



P→P' => d2'<d2

# Verifiable Multilateration

Properties:

1. *P cannot successfully claim to be at P'≠P, where* ***P' is within the triangle***
2. *M cannot convince Vs and P that P is at P'≠P where* ***P' is within the triangle***
3. *P or M can spoof a location from P to P' where P' is* ***outside the triangle***



# Verifiable Multilateration

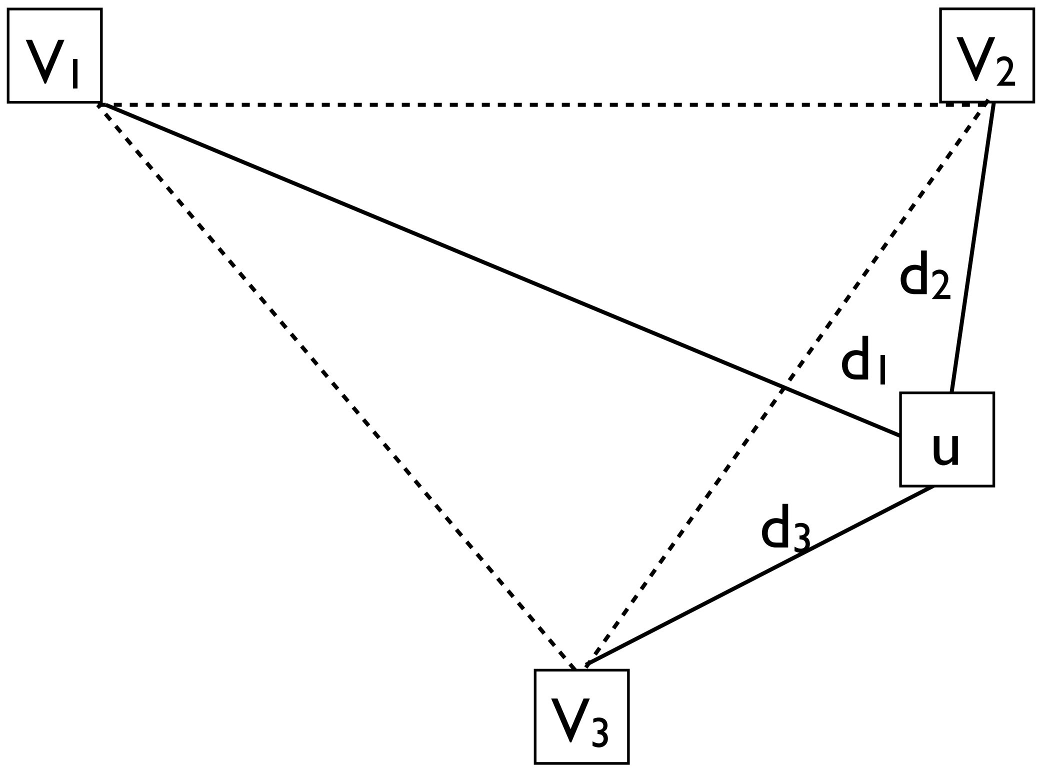
The algorithm and the errors:

- Need to be careful how the position is computed!
- Example: *Minimum Mean Square Estimate (MMSE)*

Let $f_i(x'_u, y'_u) = db_i - \sqrt{(x_i - x'_u)^2 + (y_i - y'_u)^2}$

| |
|---|
| The position of $u$ is obtained by minimizing $F(x'_u, y'_u) = \sum_{v_i \in T} f_i^2(x'_u, y'_u)$ over all estimates of $u$ |

- *Attack:*



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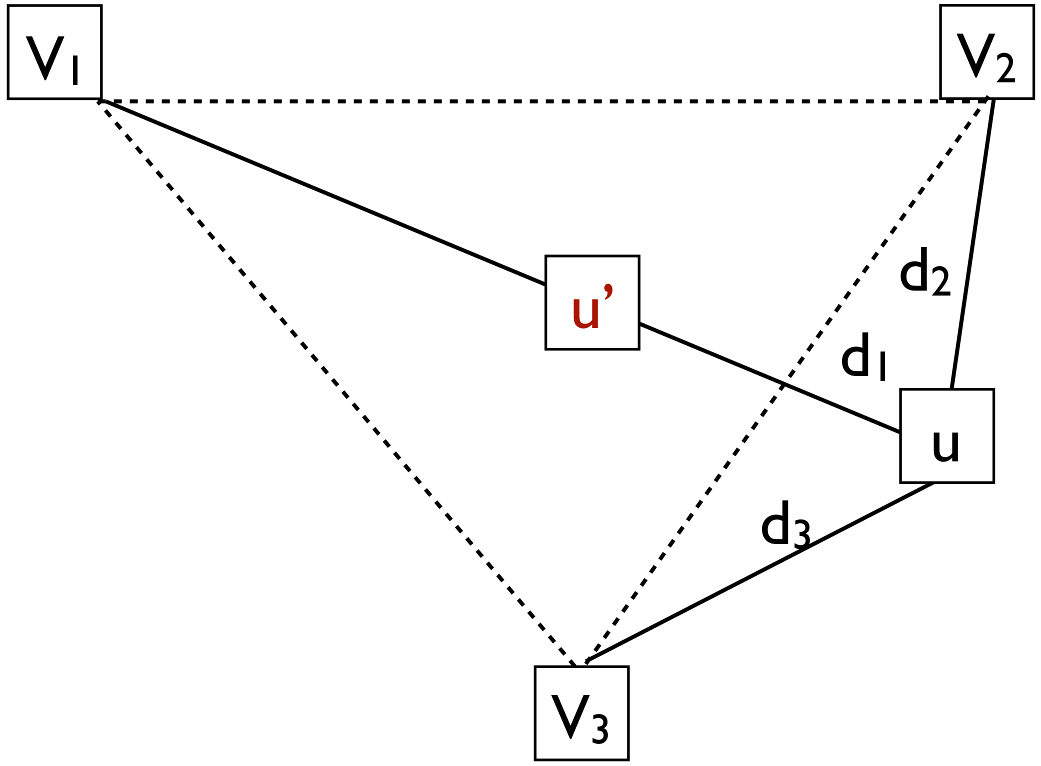

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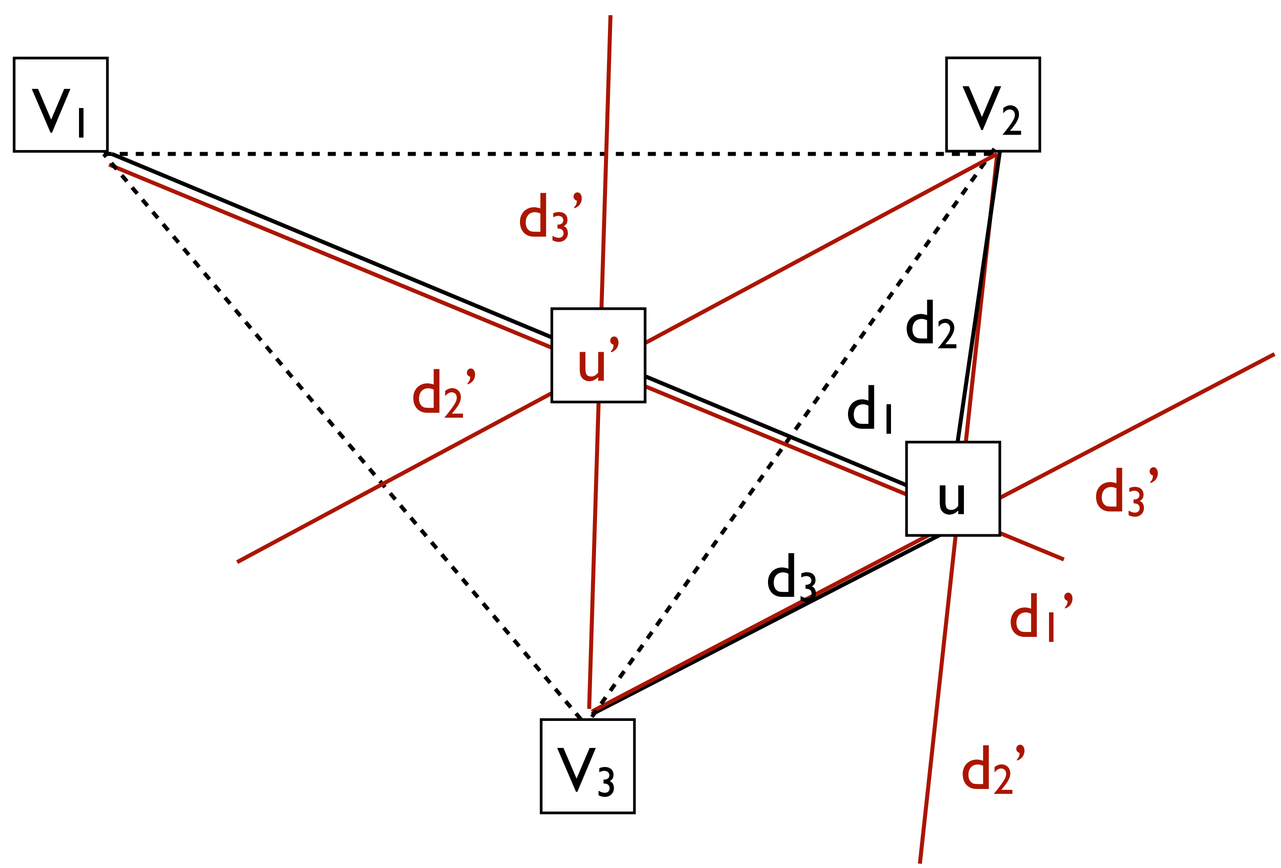

# Verifiable Multilateration

## Verifiable Multilateration Algorithm

$\mathcal{T} = \emptyset$; set of verification triangles enclosing $u$

$\mathcal{V} = \{v_1, ..., v_n\}$; set of verifiers in the power range of $u$

1 *For all* $v_i \in \mathcal{V}$, perform distance bounding from $v_i$ to $u$ and obtain $db_i$

2 With all $v_i \in \mathcal{V}$, compute the estimate $(x'_u, y'_u)$ of the position by MMSE

3 *If for all* $v_i \in \mathcal{V}$, $|db_i - \sqrt{(x_i - x'_u)^2 + (y_i - y'_u)^2}| \leq \delta$ *then*

*for all* $(v_i, v_j, v_k) \in \mathcal{V}^3$, *if* $(x'_u, y'_u) \in \Delta(v_i, v_j, v_k)$

*then* $\mathcal{T} = \mathcal{T} \cup (v_i, v_j, v_k)$

*if* $|\mathcal{T}| > 0$ *then* position is accepted and $x_u = x'_u$, $y_u = y'_u$

*else* the position is rejected

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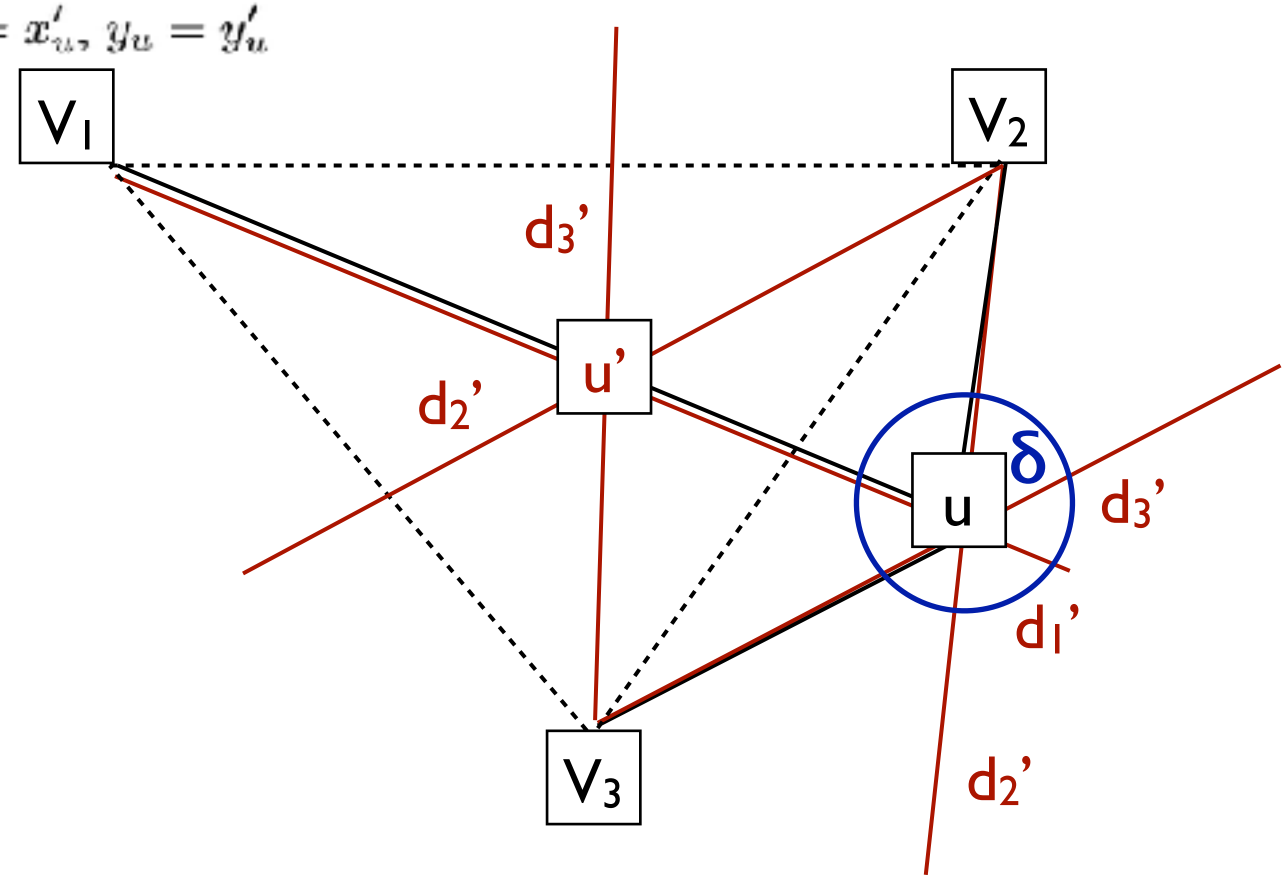
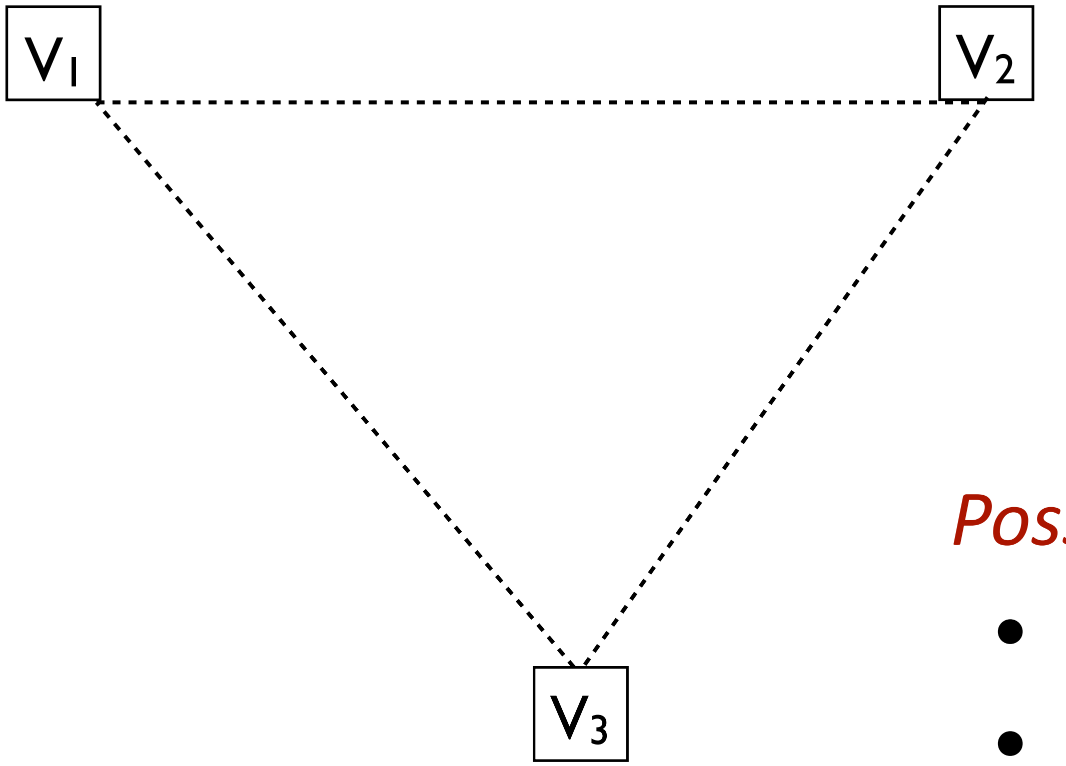


# Verifiable Multilateration

Collusion attacks (only with untrusted prover under location verification)

- *Attack:*




*Possible protections:*

- Tamper Resistance
- Device Identification

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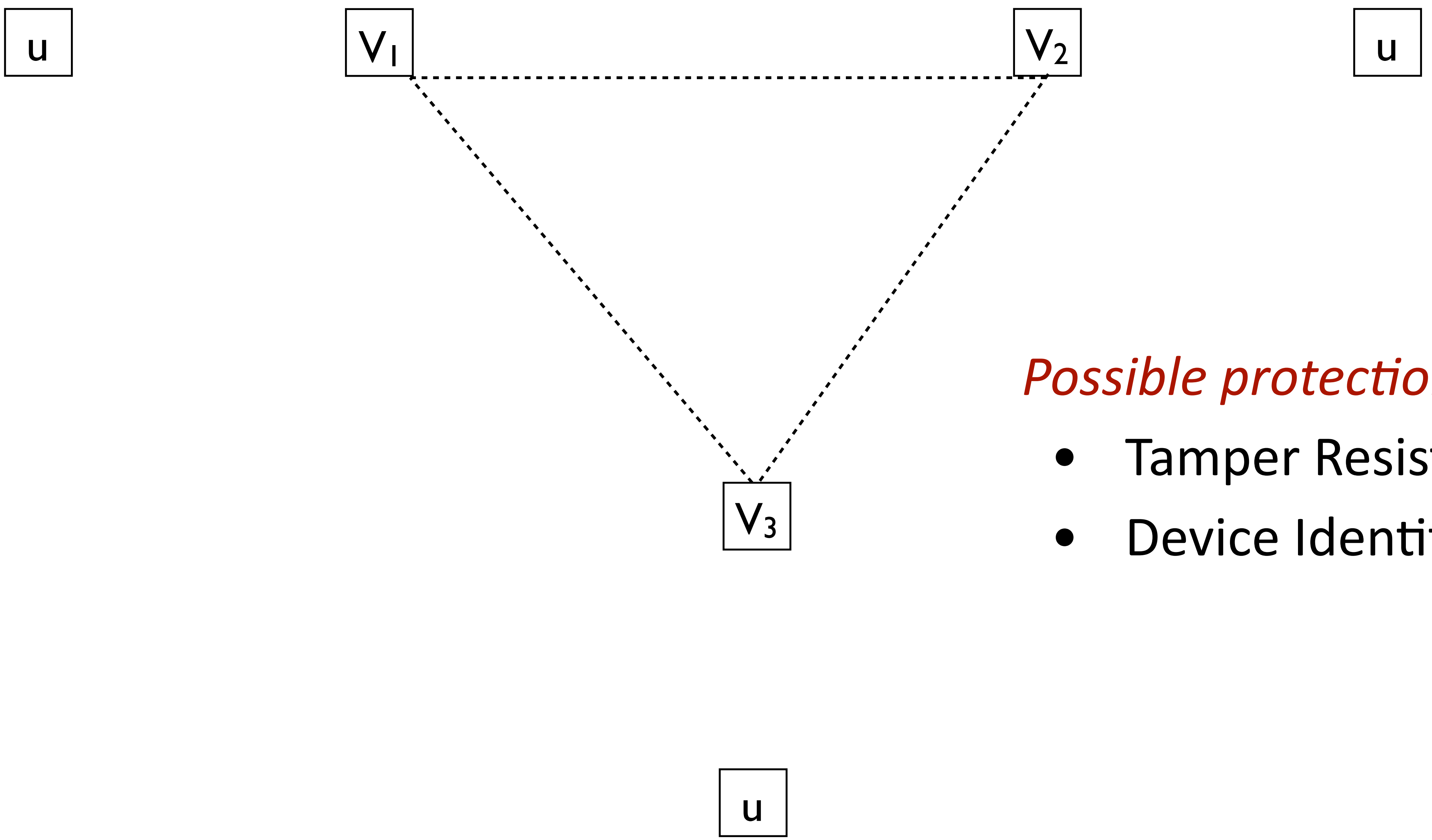


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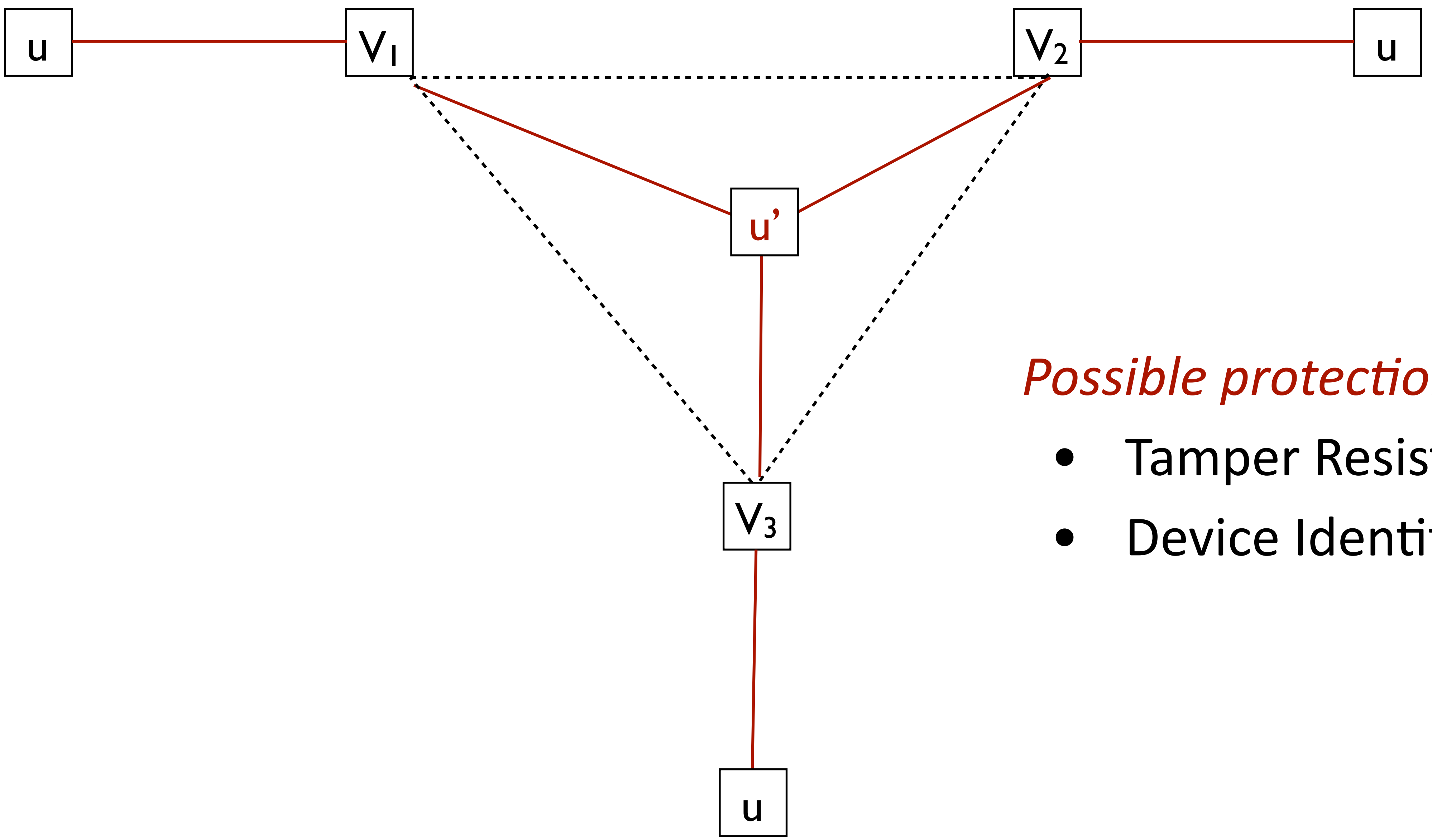


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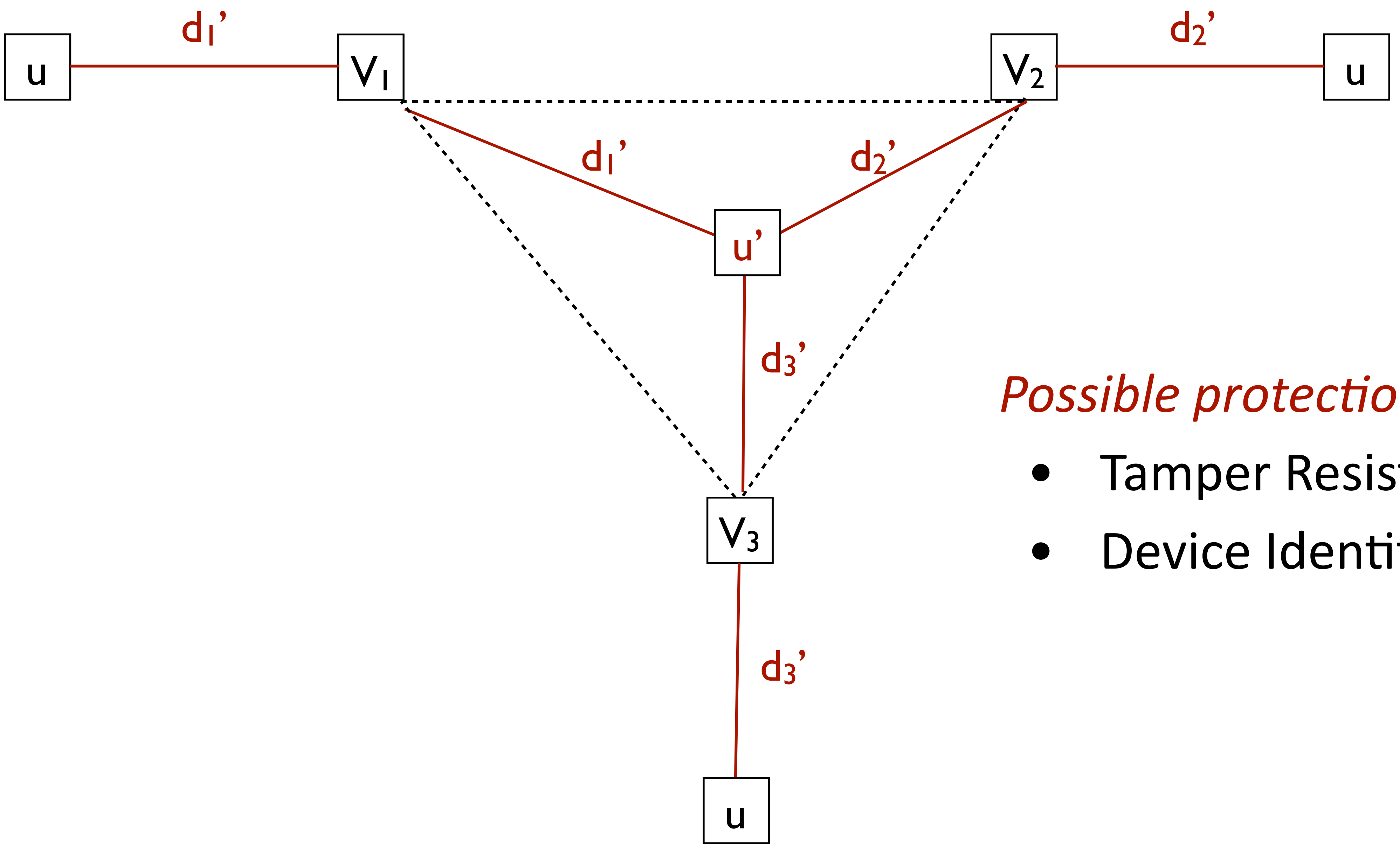


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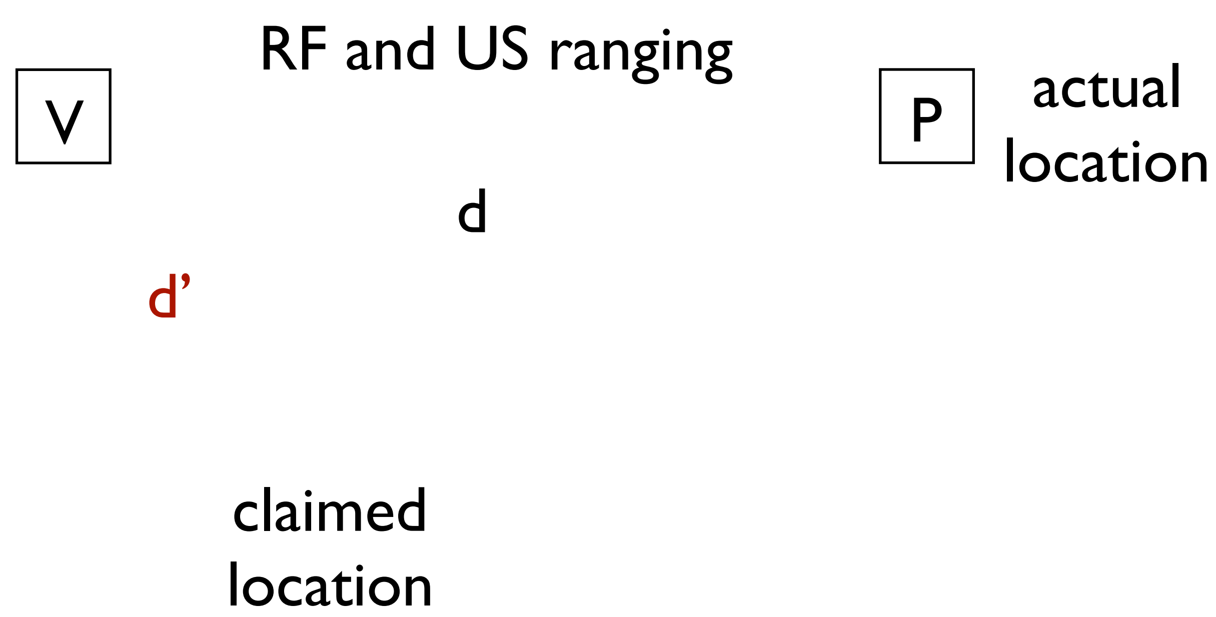
# Location Verification using Hidden and Mobile Stations *(Verifiers)*

The basic idea:

- *If the prover does not know where the verifiers are, it doesn't know how to cheat.*




*p(successful cheating)* = $p(d - d' \leq \Delta)$

where $\Delta$ is the ranging/localization accuracy

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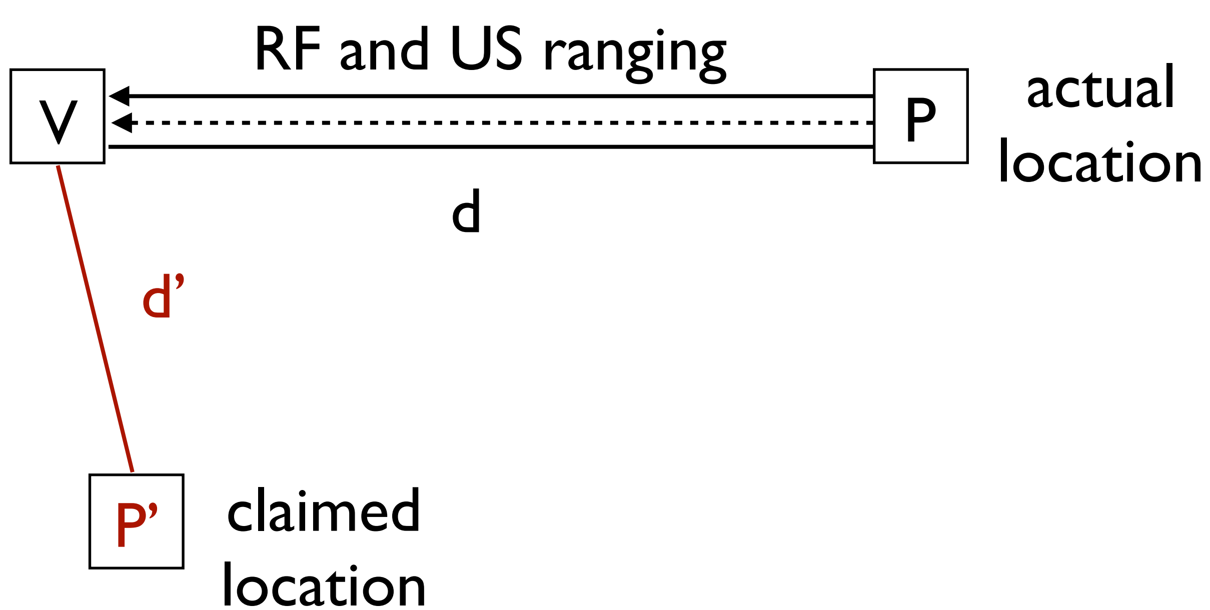


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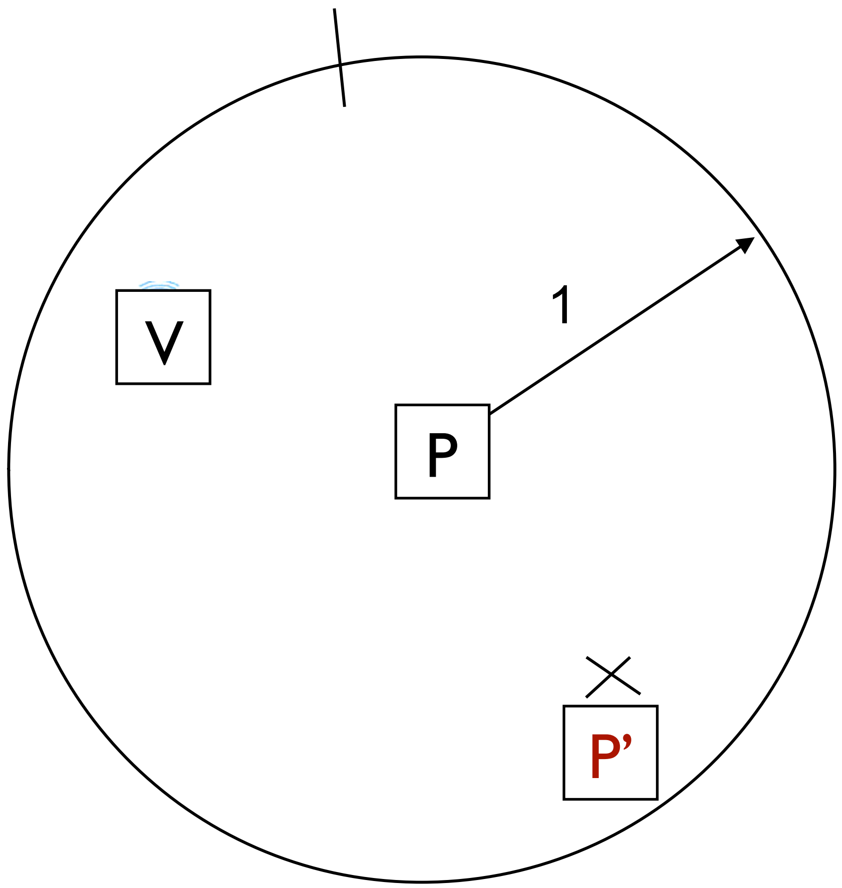
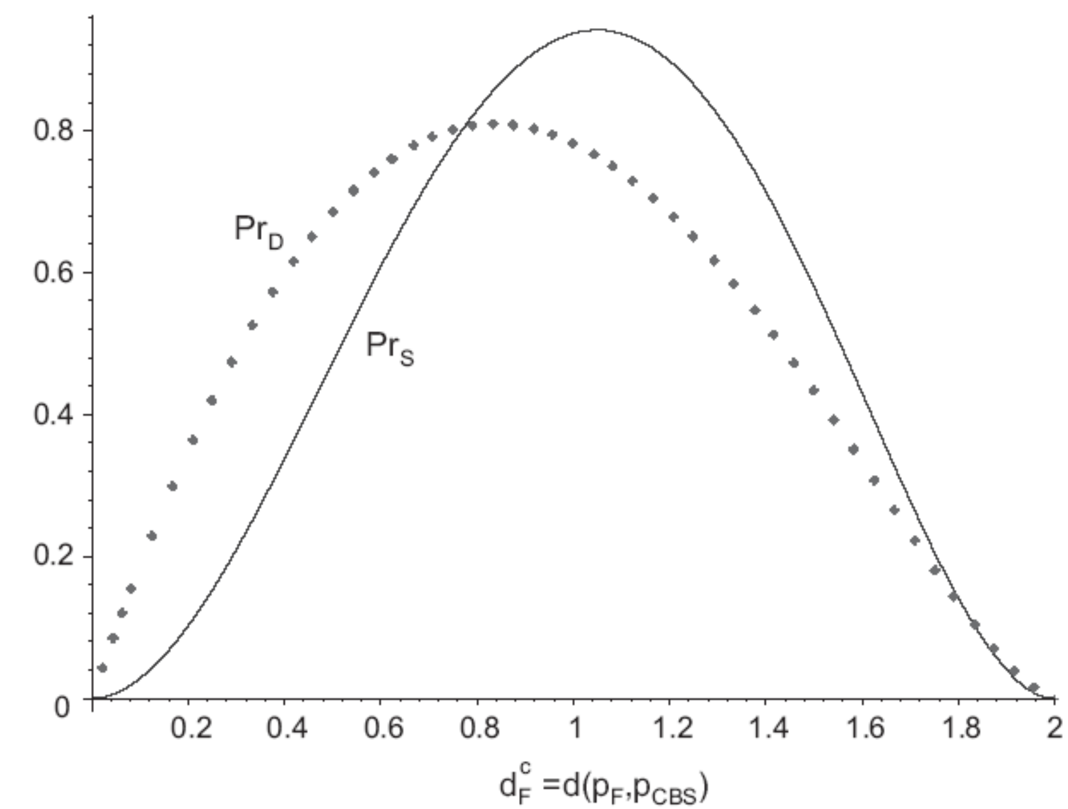



**Observation 1:**




not all distances are equally likely

- Not all locations are equally easy to fake (center is the 'easiest').
- *Problems if the attacker knows where verifiers cannot be.*

# Summary (on secure localization)

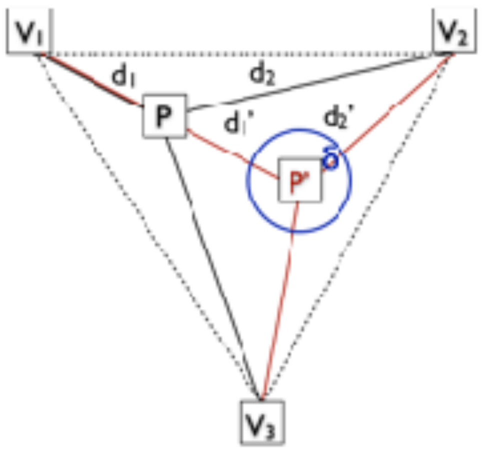
Main ideas

- Use time as a side-channel (e.g., distance bounding)
- Use hidden verifier locations
- Use spread spectrum communication (hide the signals such that they cannot be manipulated - in time)

- References:
  - Verifiable Multilateration:
    S. Capkun, J. P. Hubaux, Secure positioning in wireless networks, IEEE Journal on Selected Areas in Communications: Special Issue on Security in Wireless Ad Hoc Networks, February 2006.
  - http://www.syssec.ethz.ch/research/spot

# Summary

- Secure Localization / Location Verification is a fascinating area
- Brings up interesting interactions between logical and physical layer
- New challenges in formal protocol analysis




- Can be used for Secure Localization and Location Verification
- Numerous Applications
  - Physical and Logical Access Control, Anti-Spoofing, Protection of Networking Functions, ...