Wireless Network Security

Lecture 5

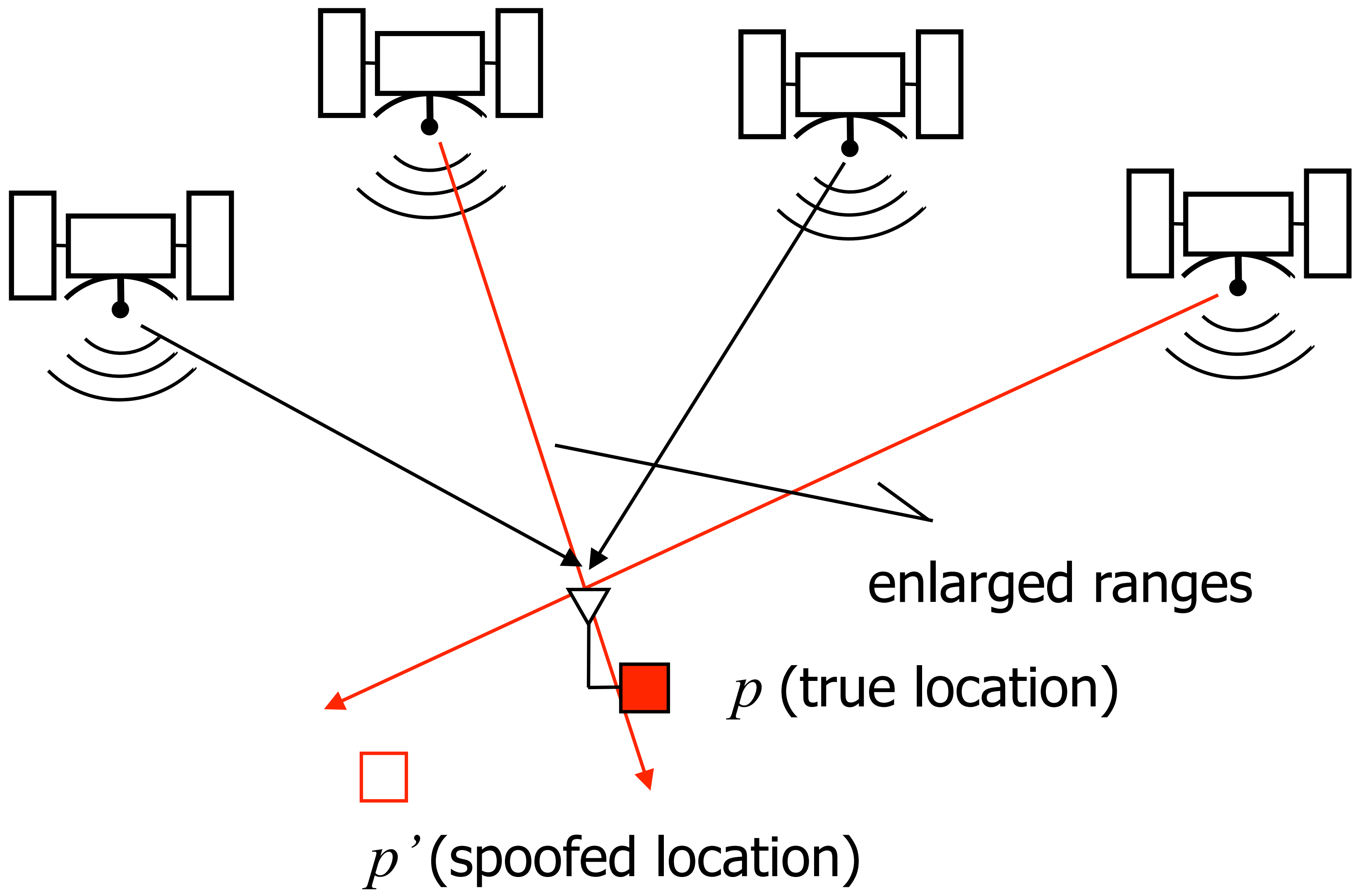
Secure Proximity Verification

Srdjan Čapkun

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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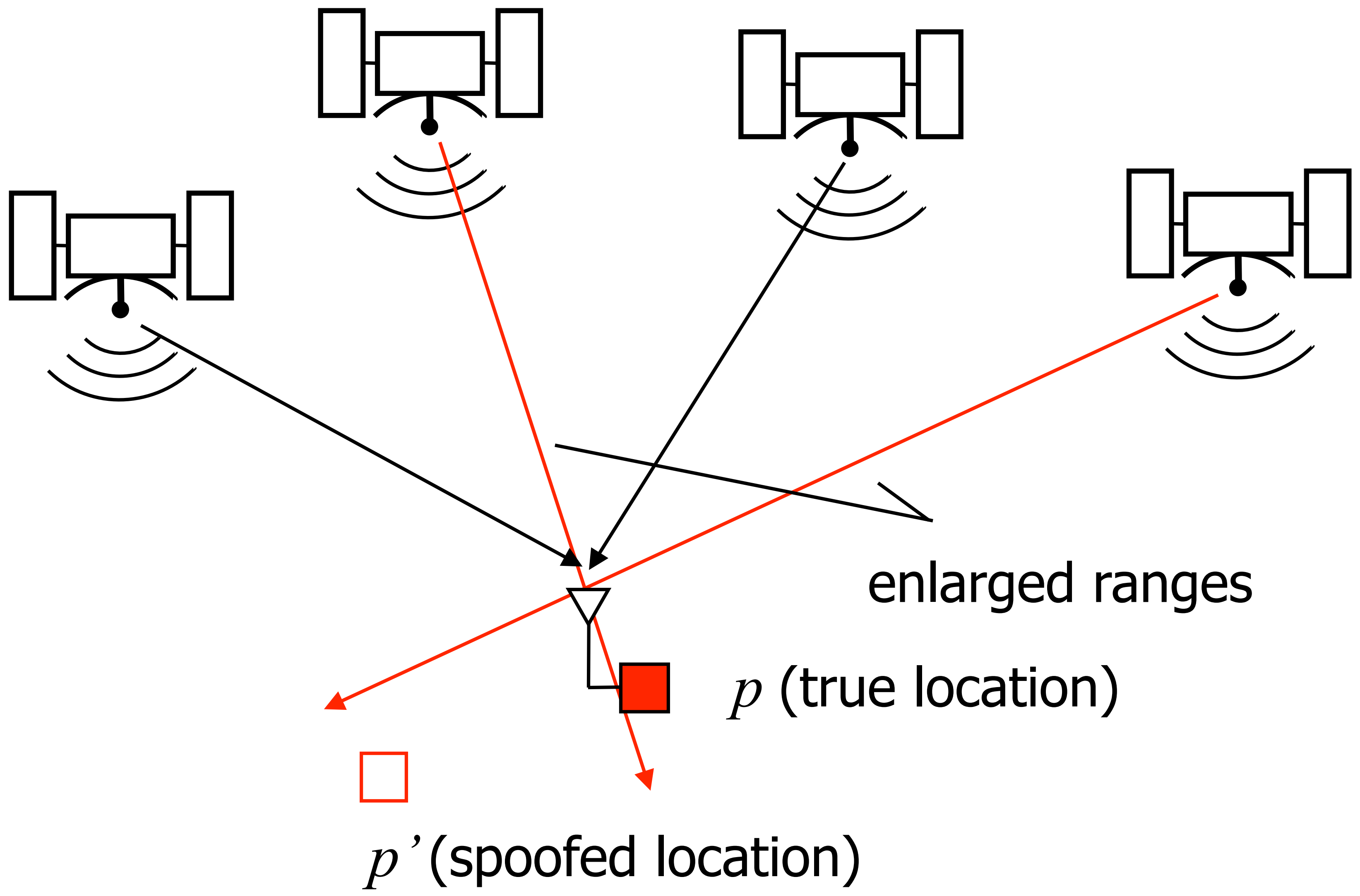
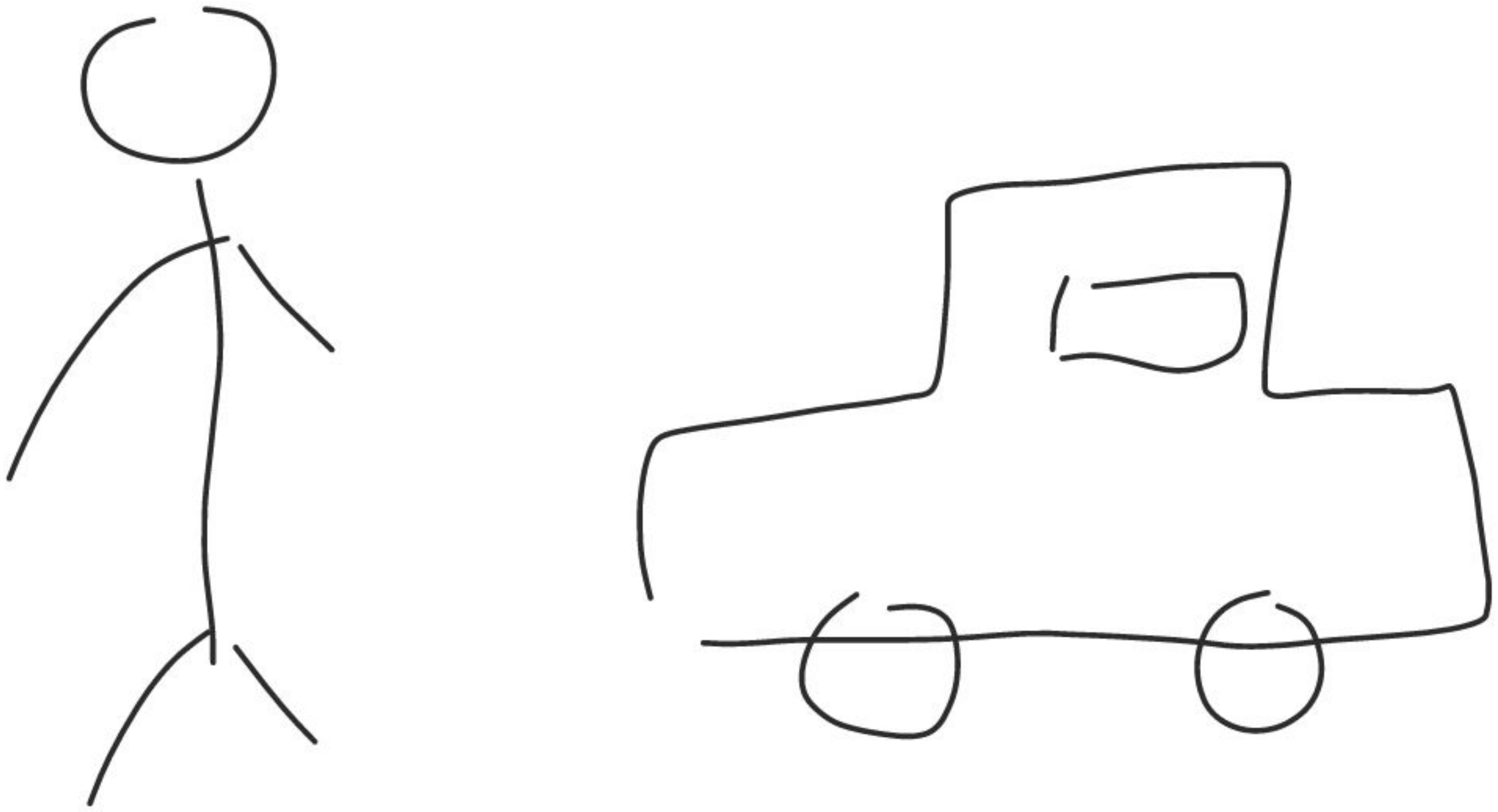
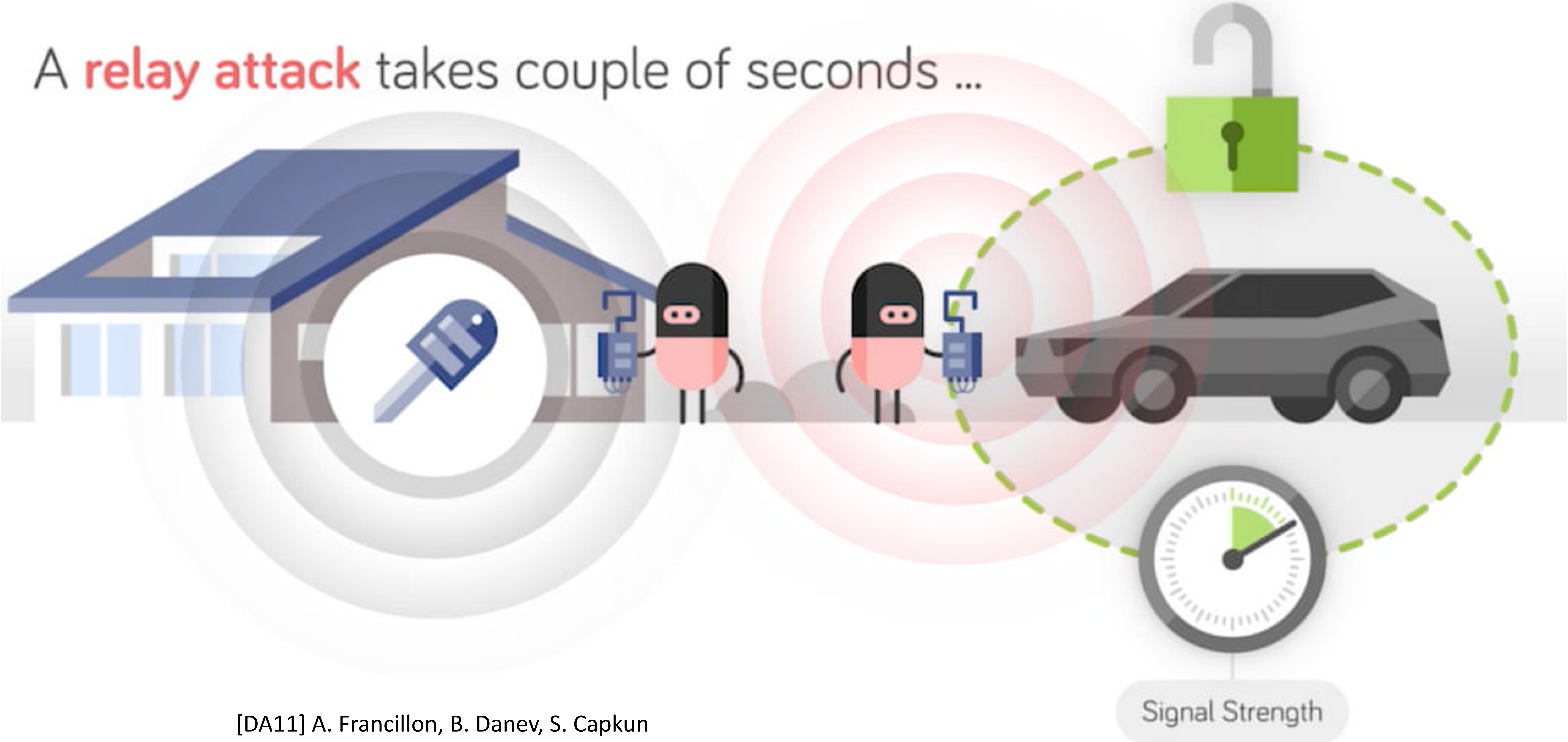


- Secure positioning requires either:
  - bidirectional communication ***or***
  - communication from the device to the infrastructure

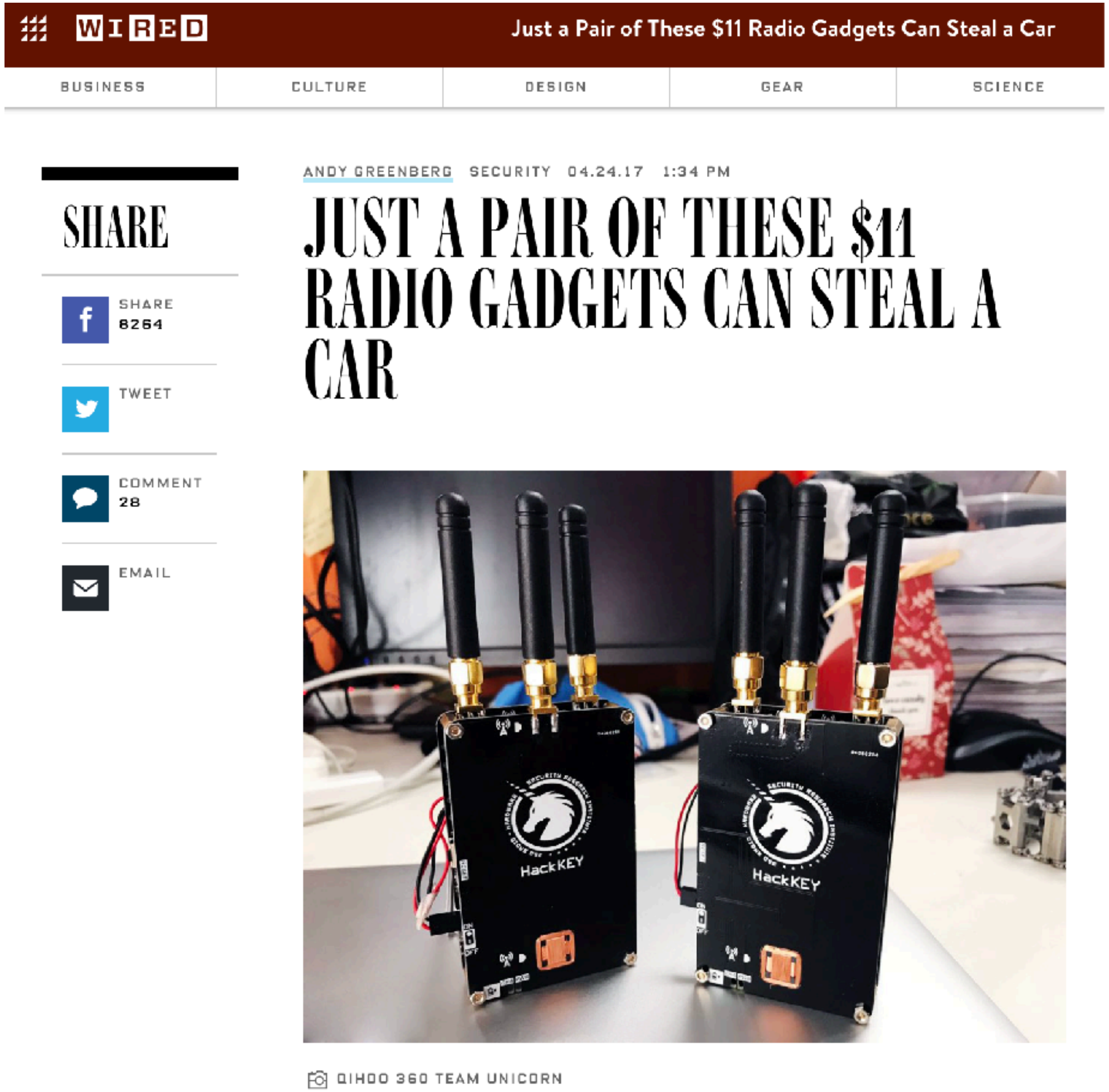
Recommended Readings

- **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.)





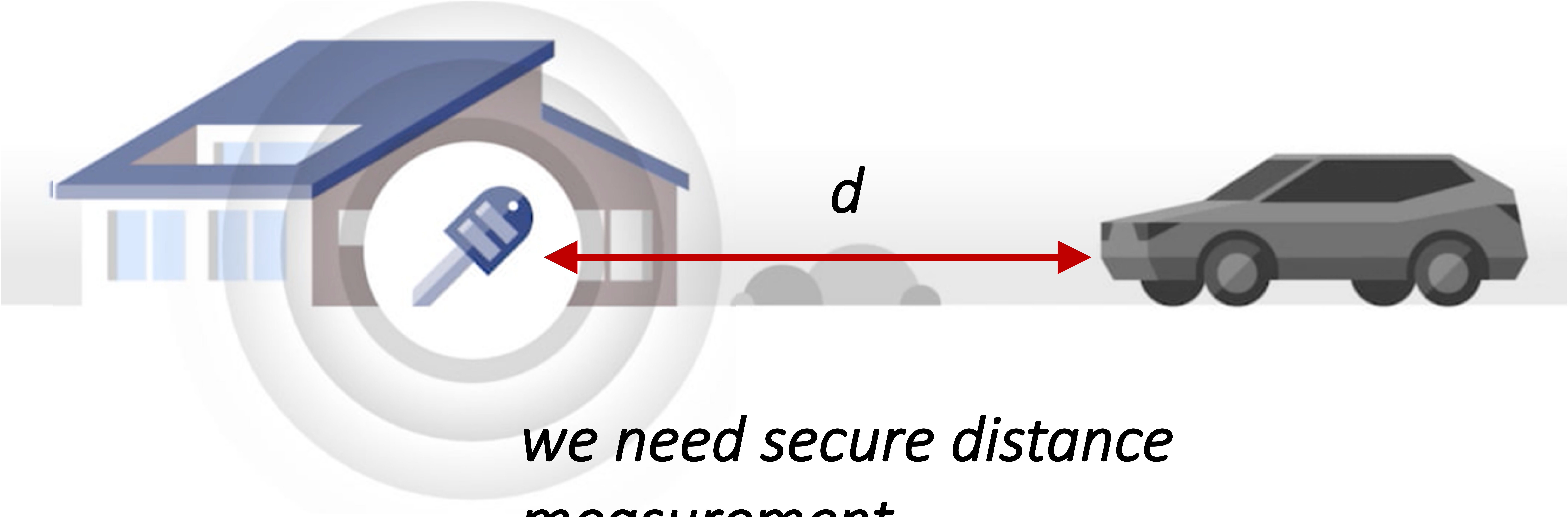
[DA11] A. Francillon, B. Danev, S. Capkun
Relay Attacks on Passive Keyless Entry and Start Systems in Modern Cars, NDSS 2011



ANDY GREENBERG SECURITY 04.24.17 1:34 PM

JUST A PAIR OF THESE $11 RADIO GADGETS CAN STEAL A CAR

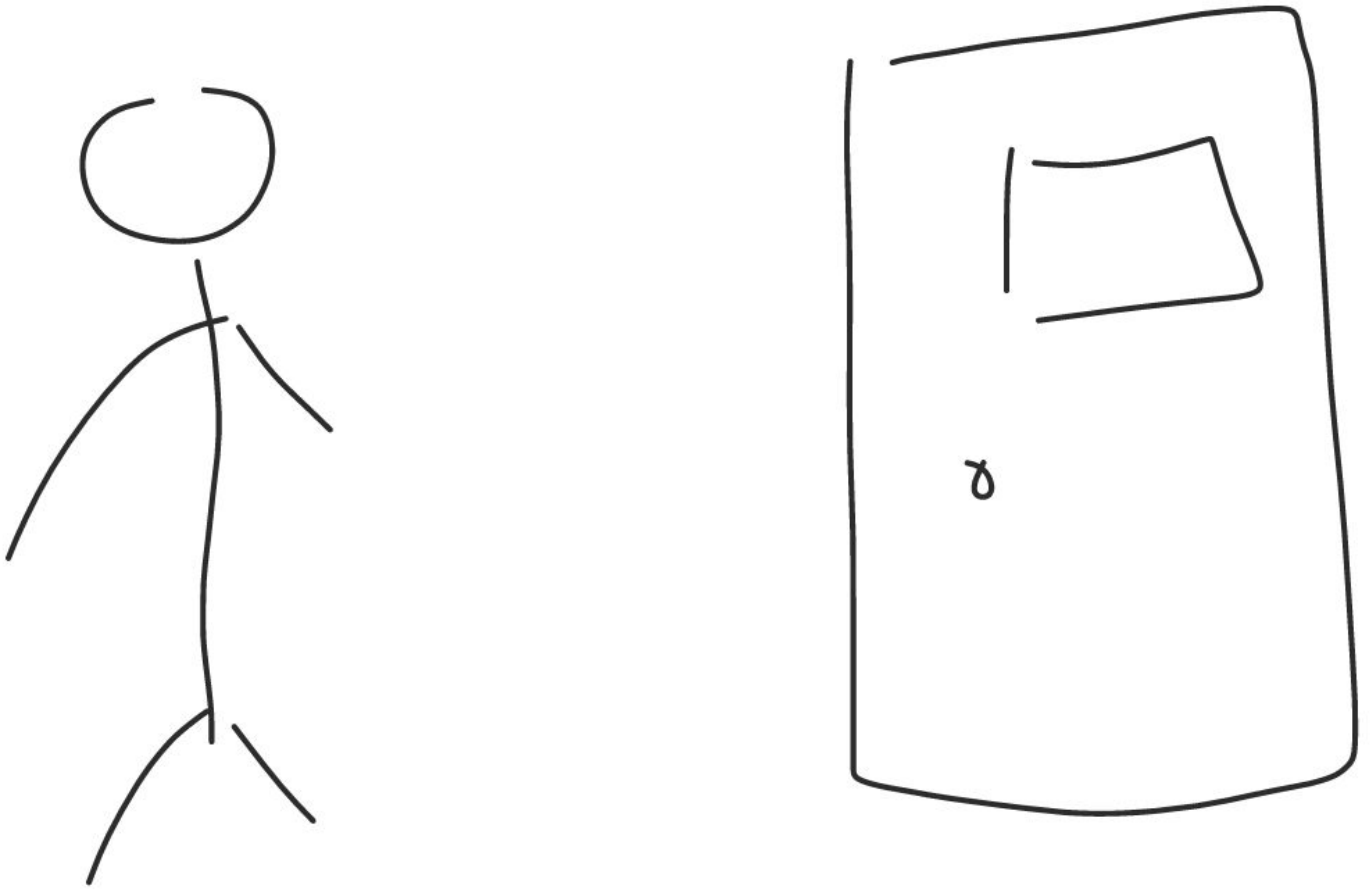
QIHOO 360 TEAM UNICORN

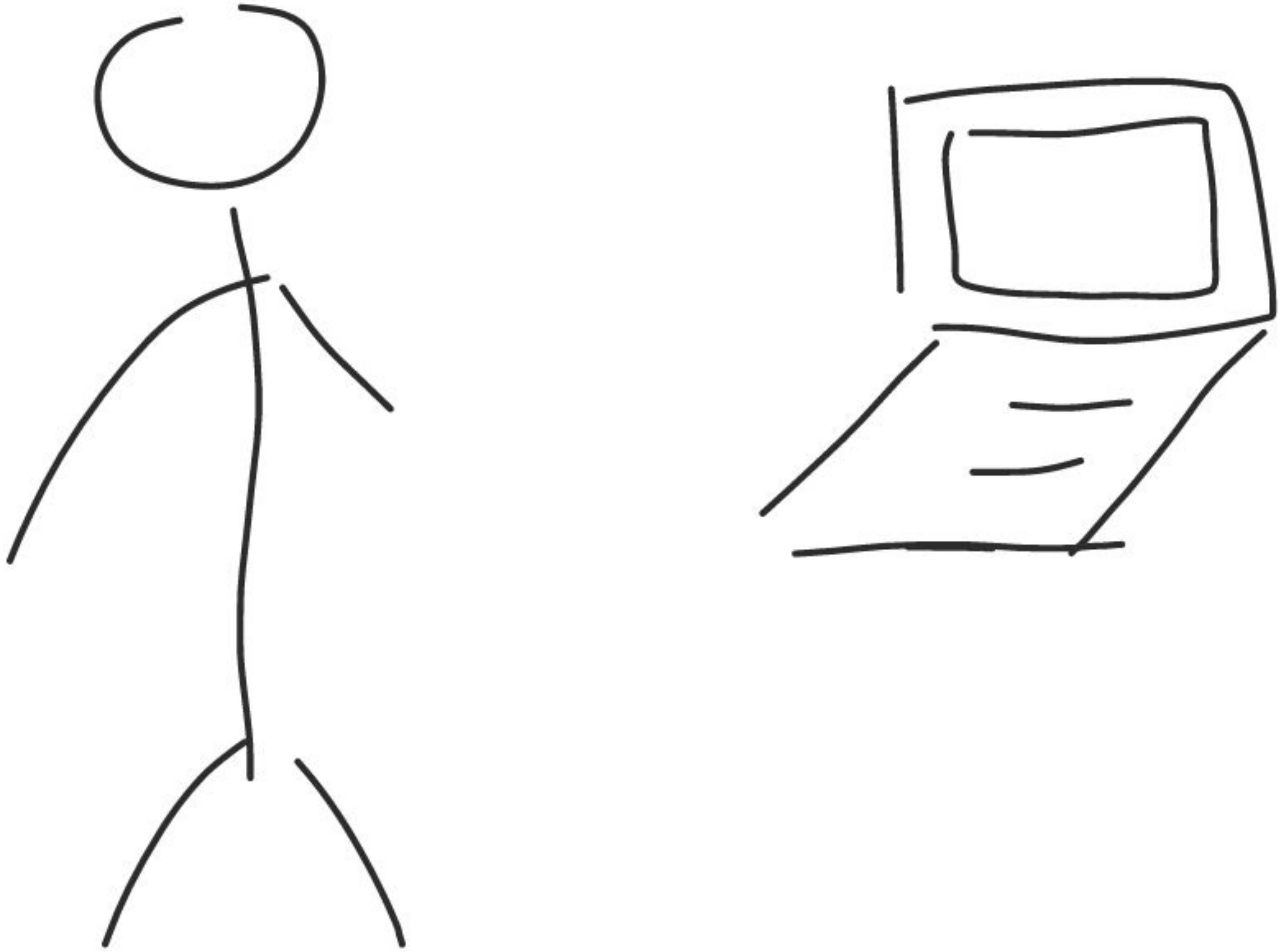


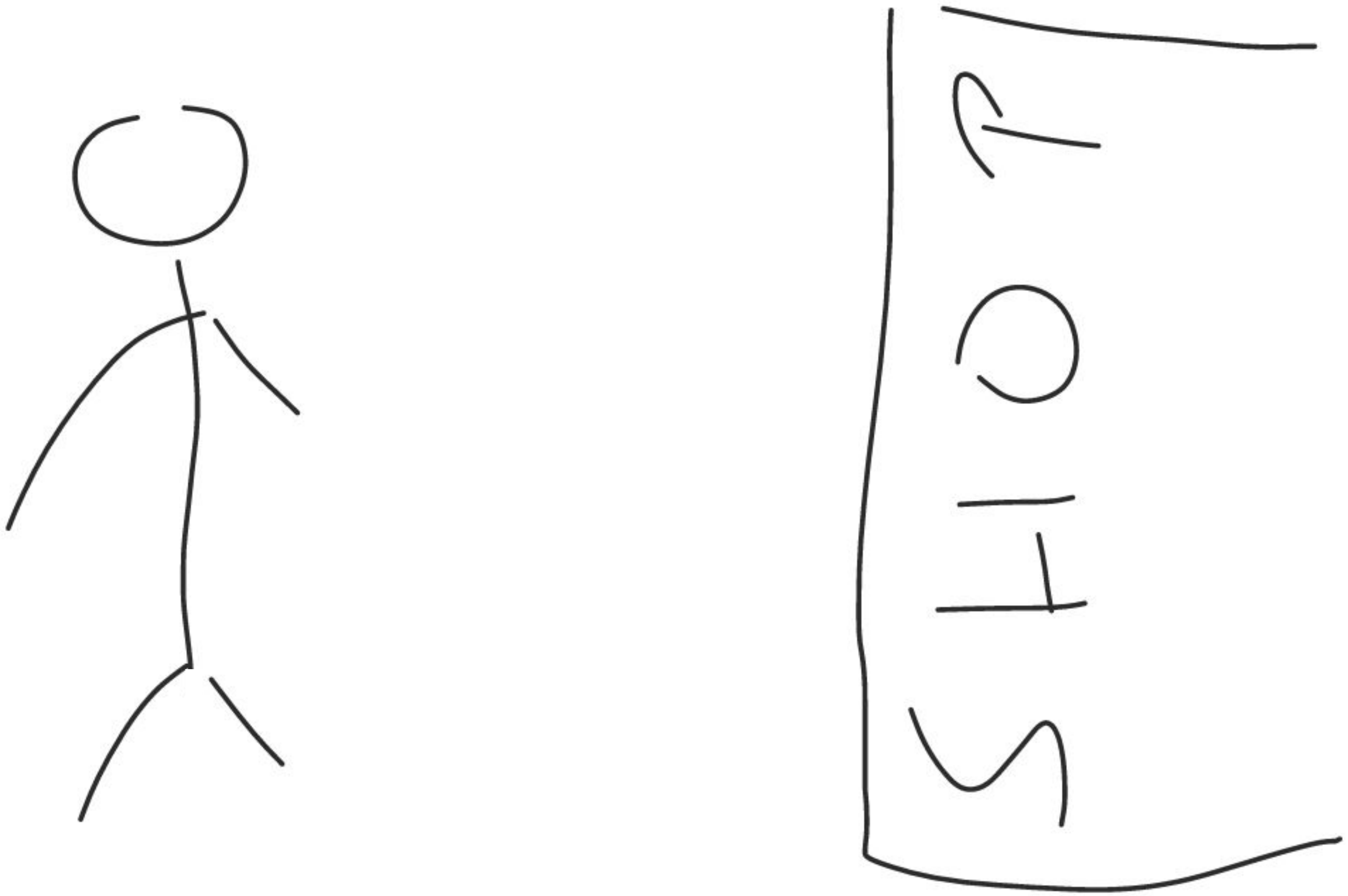
we need secure distance measurement

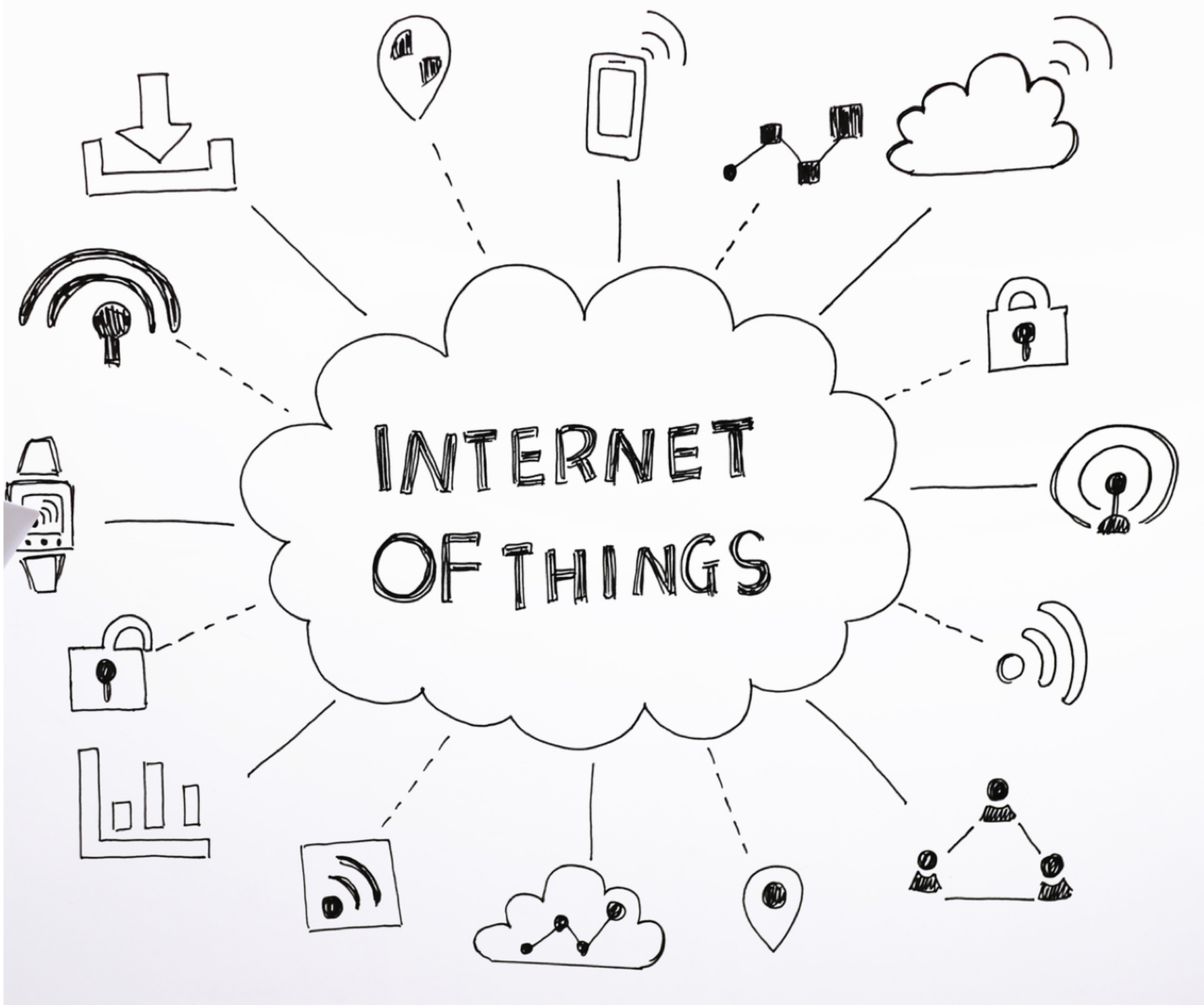

09-25-2017 Mon 01:01:41
Camera 01
WEST MIDLANDS POLICE


09-25-2017 Mon 01:01:41
Camera 01
WEST MIDLANDS POLICE






SHOP


INTERNET
OF THINGS

need to know where other objects/people are

need to know where we are

need to know where <u>other objects/people</u> are

need to know where <u>we</u> are

<u>securely</u>

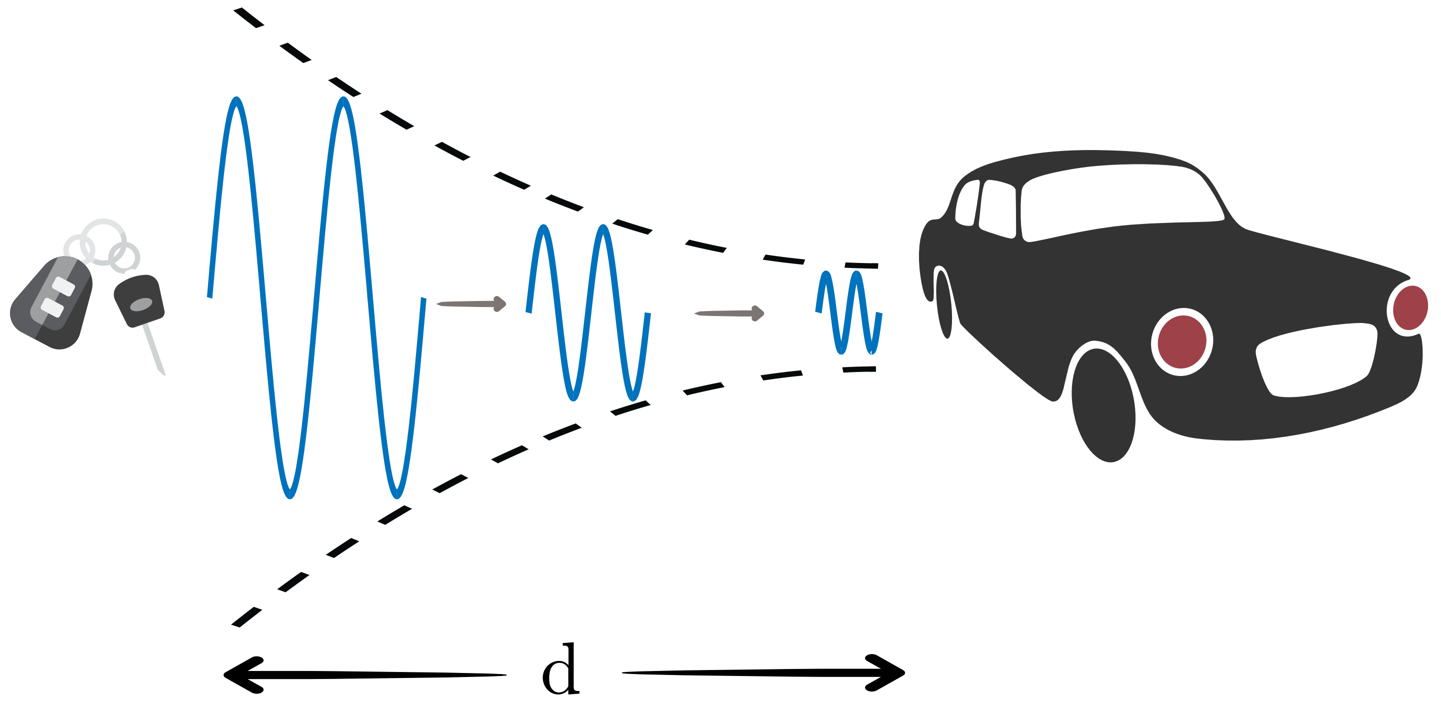
Can we build distance bounding HW?

Can it be cheap and efficient?

Can we build distance bounding HW?

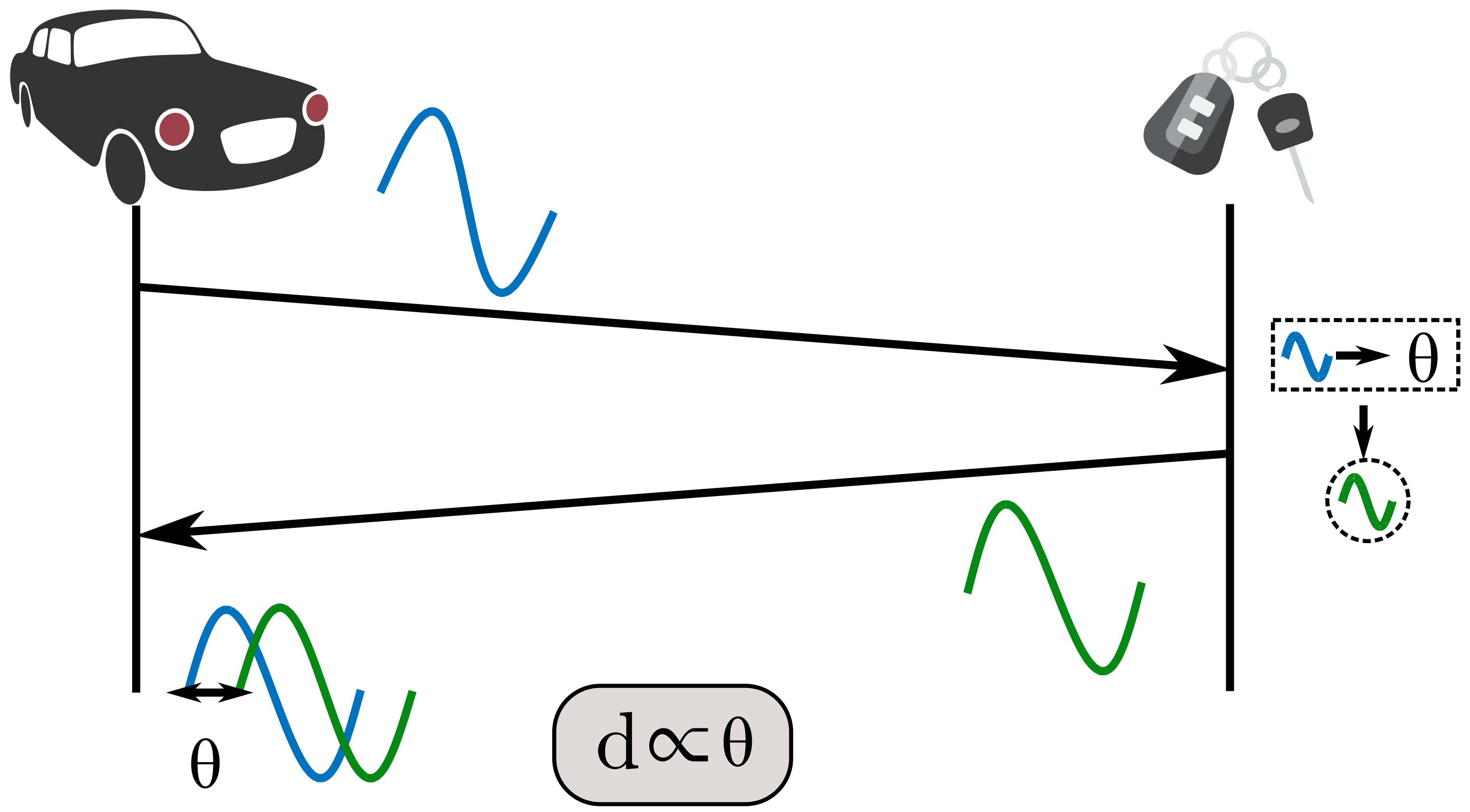
Can it be cheap and efficient?

Estimating Proximity



Received Signal Strength

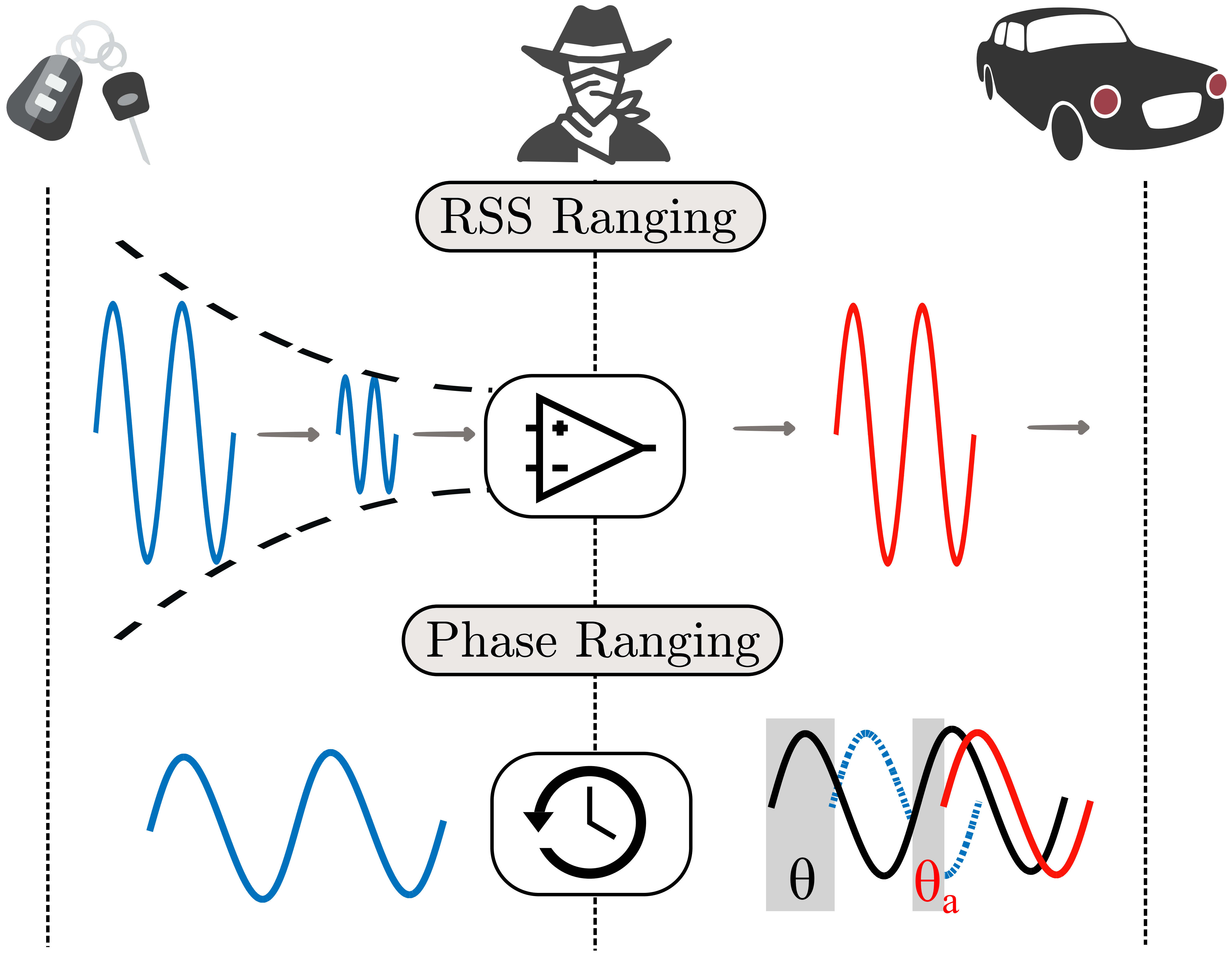
$$d = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t G_r}{P_r}}$$



Carrier Phase Ranging

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

Attacking Proximity

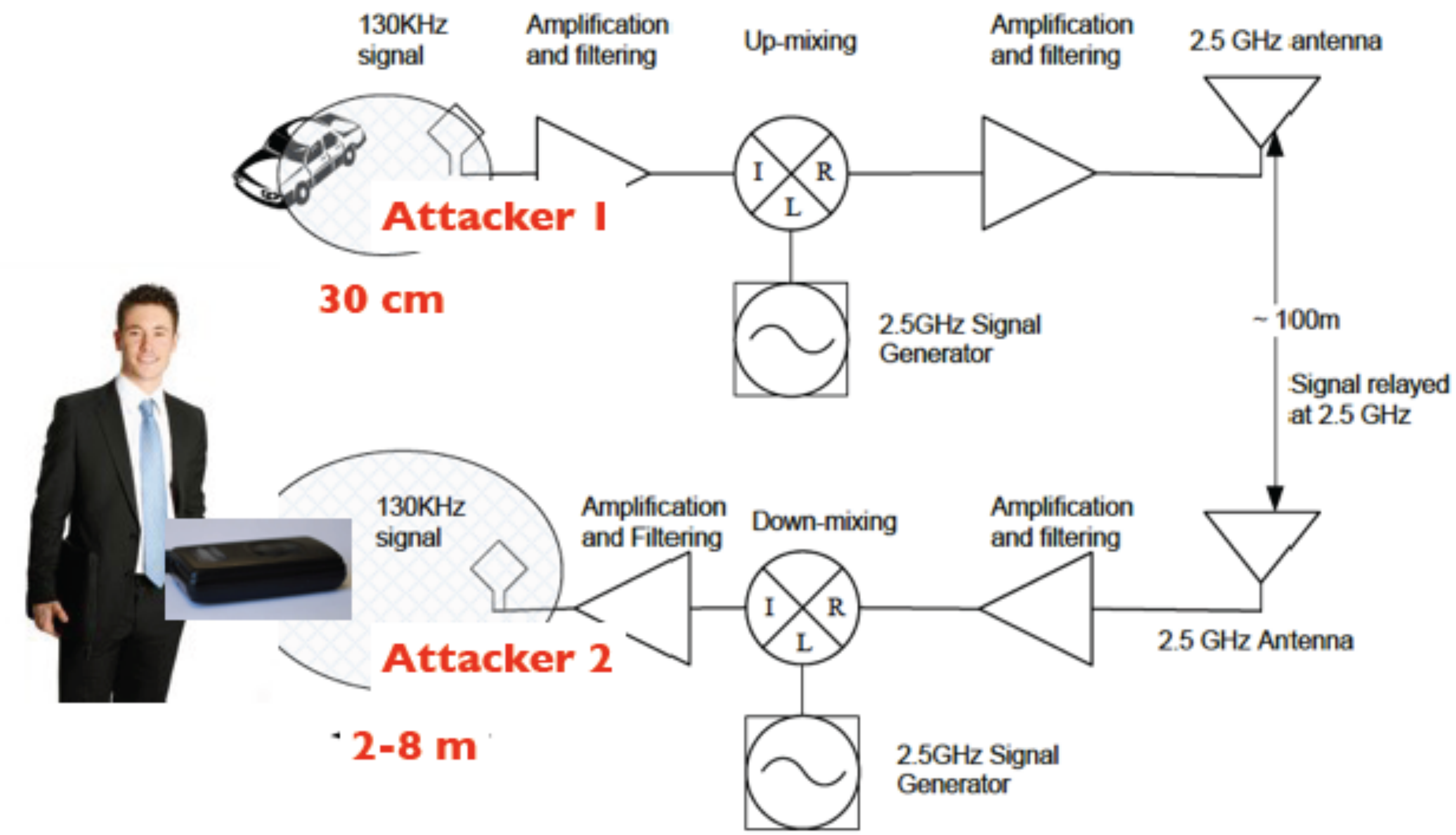


Example: PKES

(deployed by all major car manufacturers)

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

- *Relay attack [FrancillonNDSS11]*

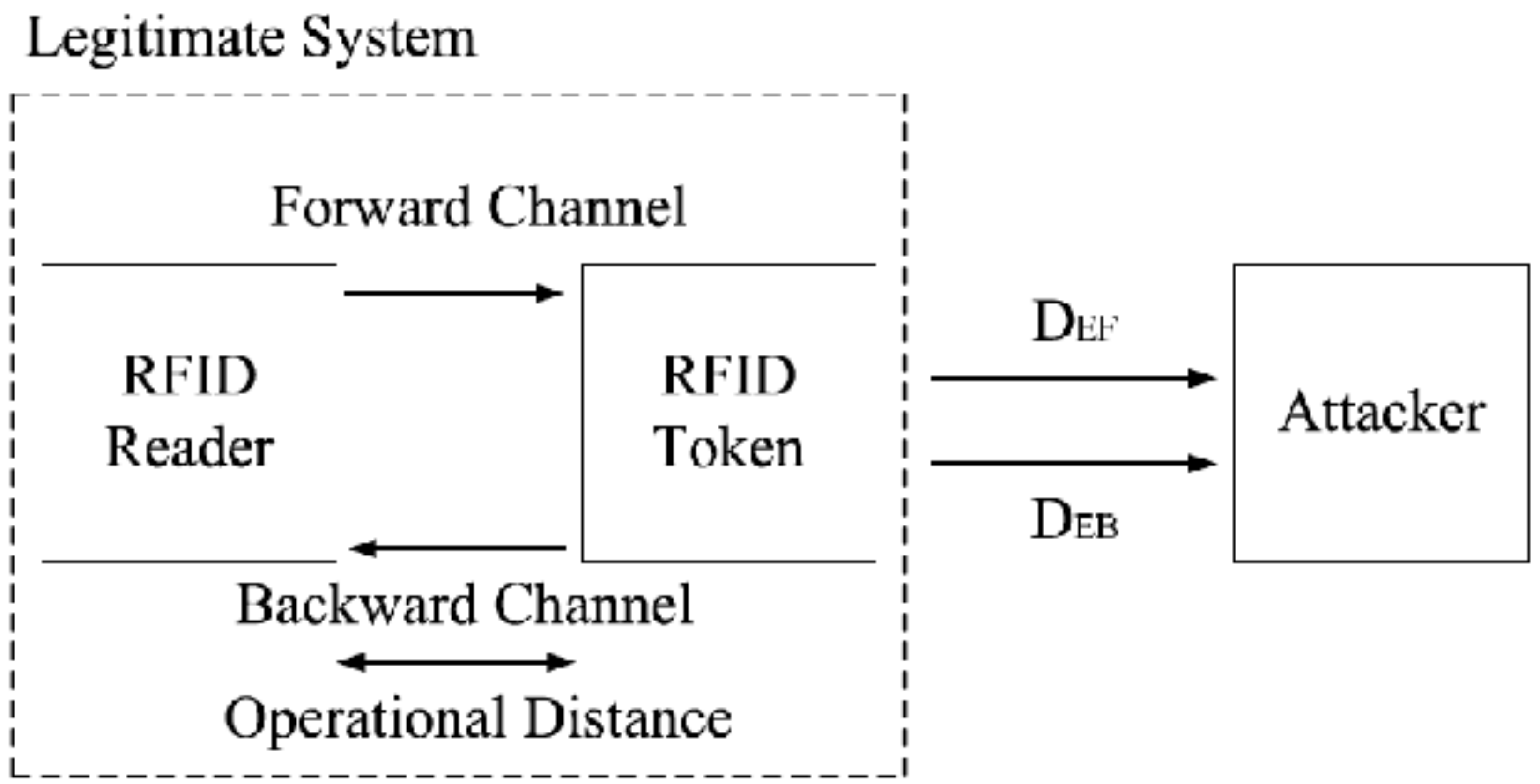


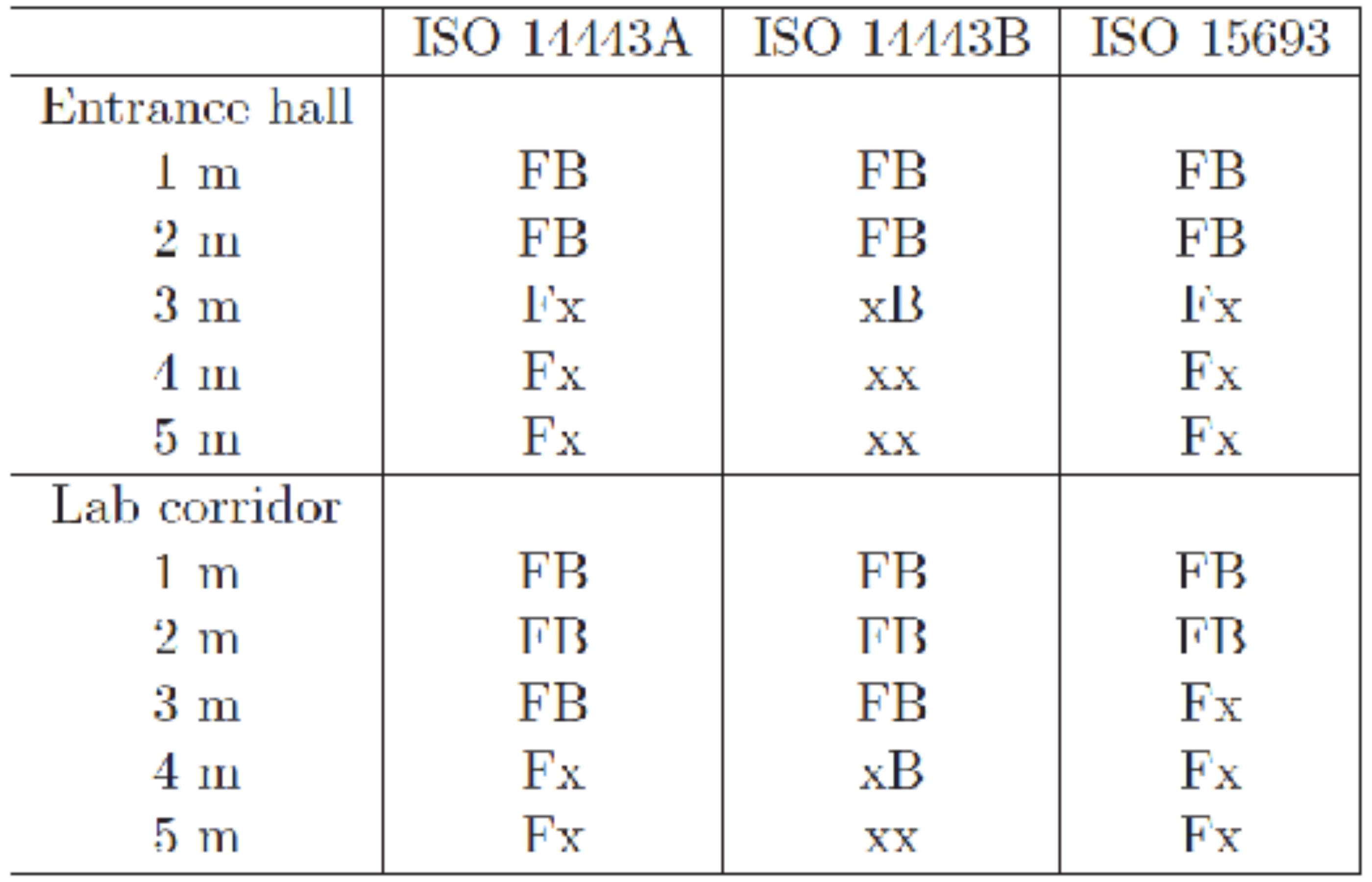
- Tested on 10 car models from 8 manufacturers
- Manufacturers are now redesigning Entry and Start Systems

Example: RFID / NFC communication

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

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

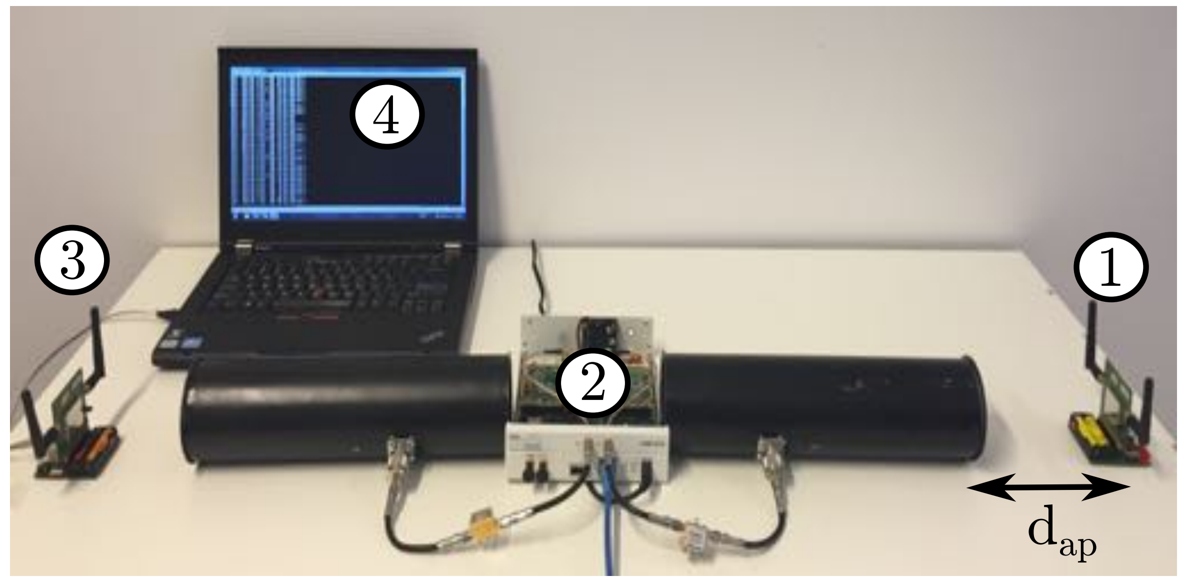


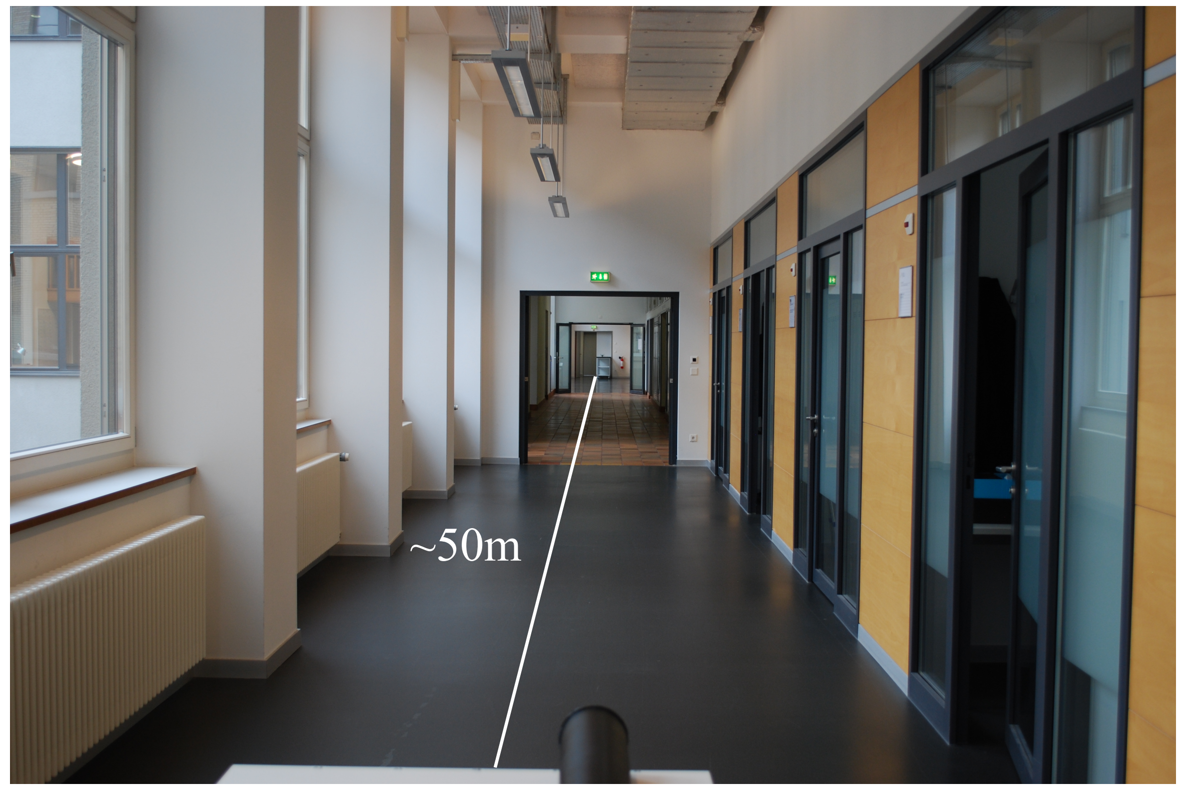


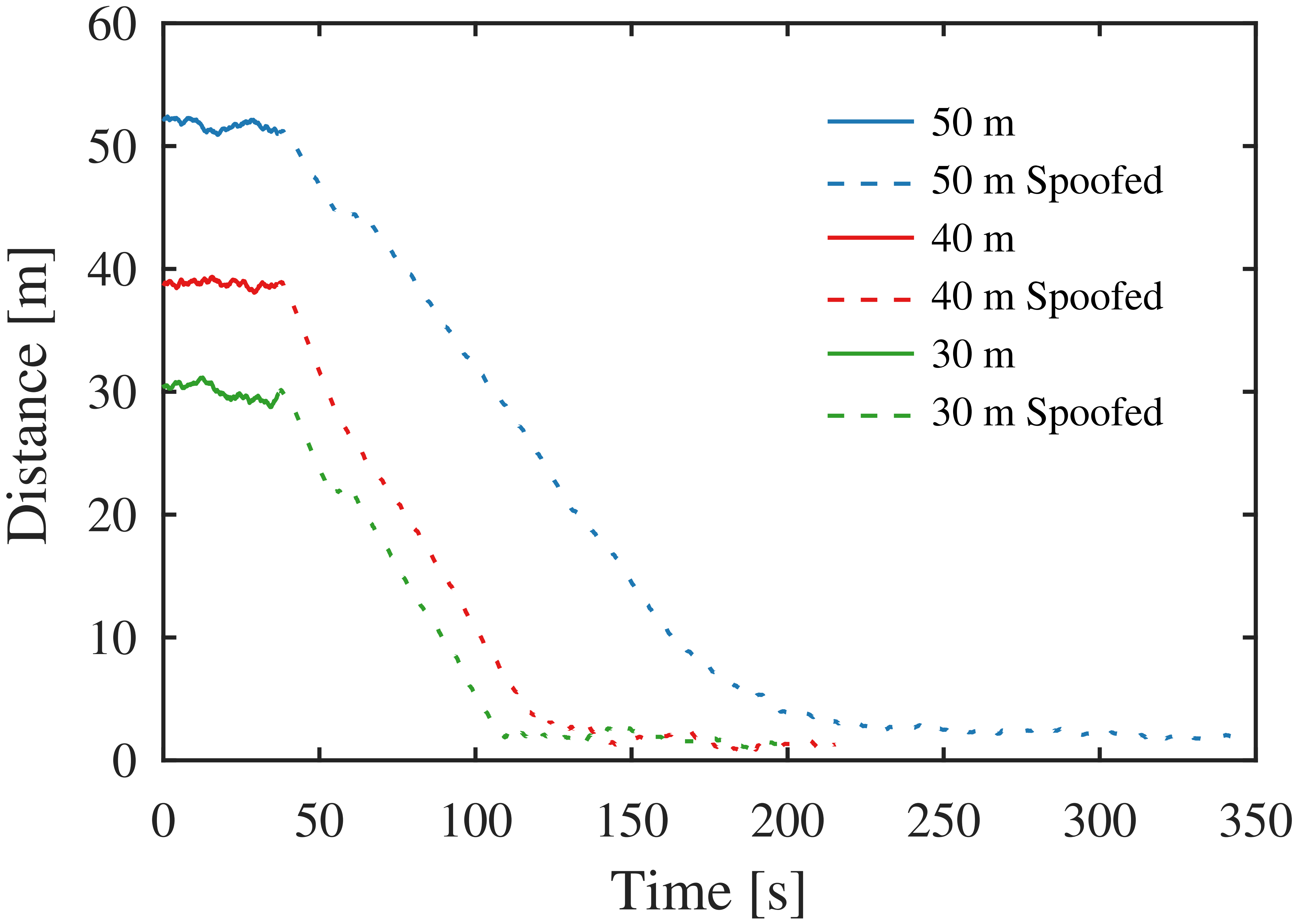
	ISO 14443A	ISO 14443B	ISO 15693
Entrance hall			
1 m	FB	FB	FB
2 m	FB	FB	FB
3 m	Fx	xB	Fx
4 m	Fx	xx	Fx
5 m	Fx	xx	Fx
Lab corridor			
1 m	FB	FB	FB
2 m	FB	FB	FB
3 m	FB	FB	Fx
4 m	Fx	xB	Fx
5 m	Fx	xx	Fx

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

Attacking Phase Ranging Systems





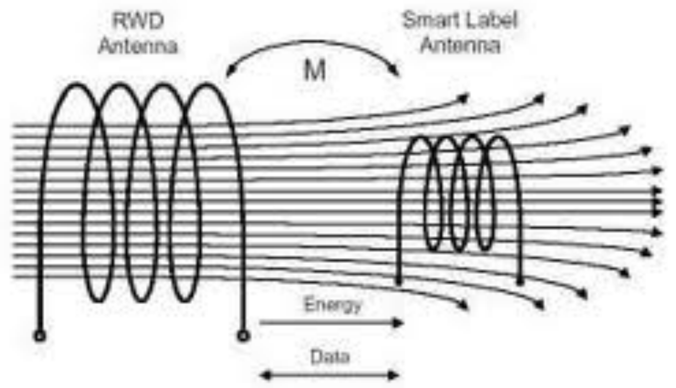


Hildur Ólafsdóttir, Aanjhan Ranganathan, and Srdjan Capkun. "On the Security of Carrier Phase-based Ranging." In ***International Conference on Cryptographic Hardware and Embedded Systems*****, 2017**

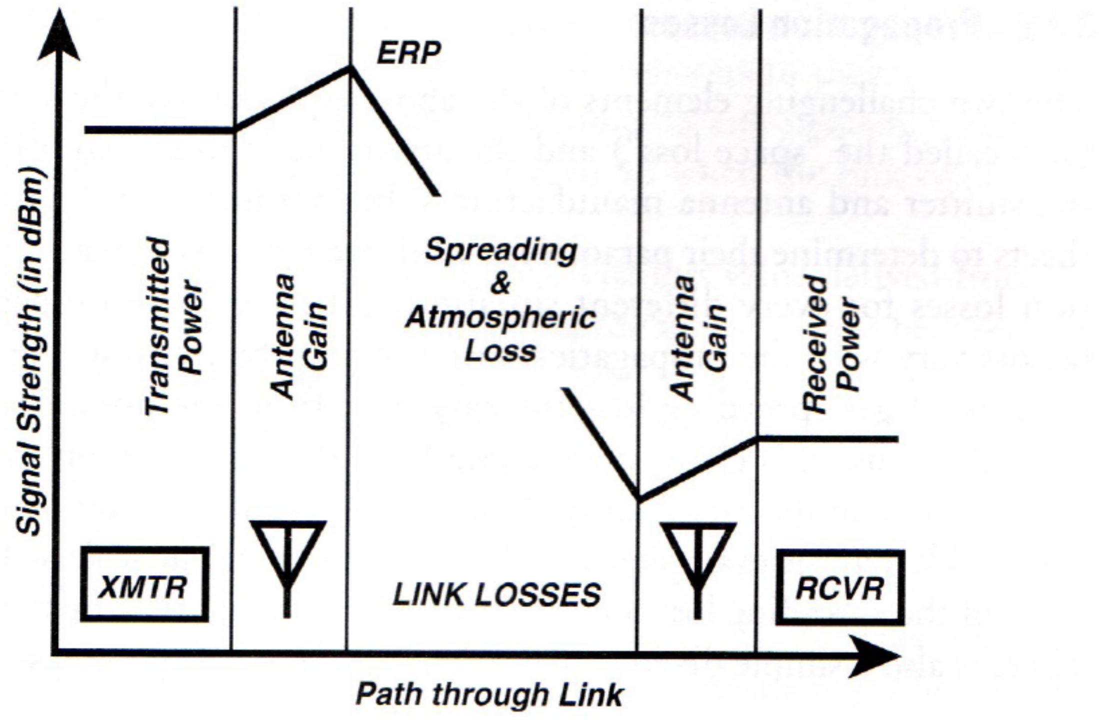
Secure Proximity Verification?

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.

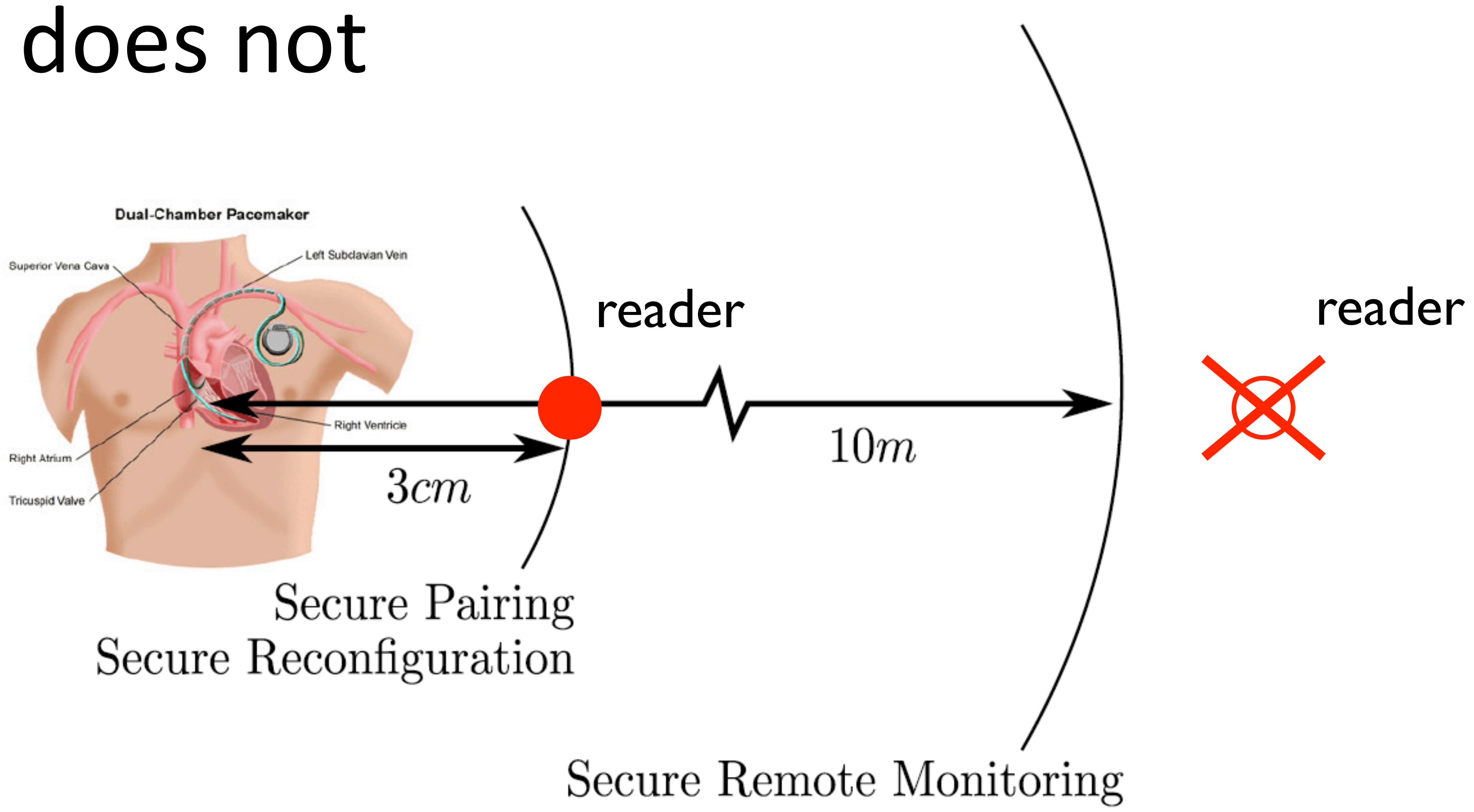
- *We need a difficult problem to hold on to.*

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

Secure Proximity Verification

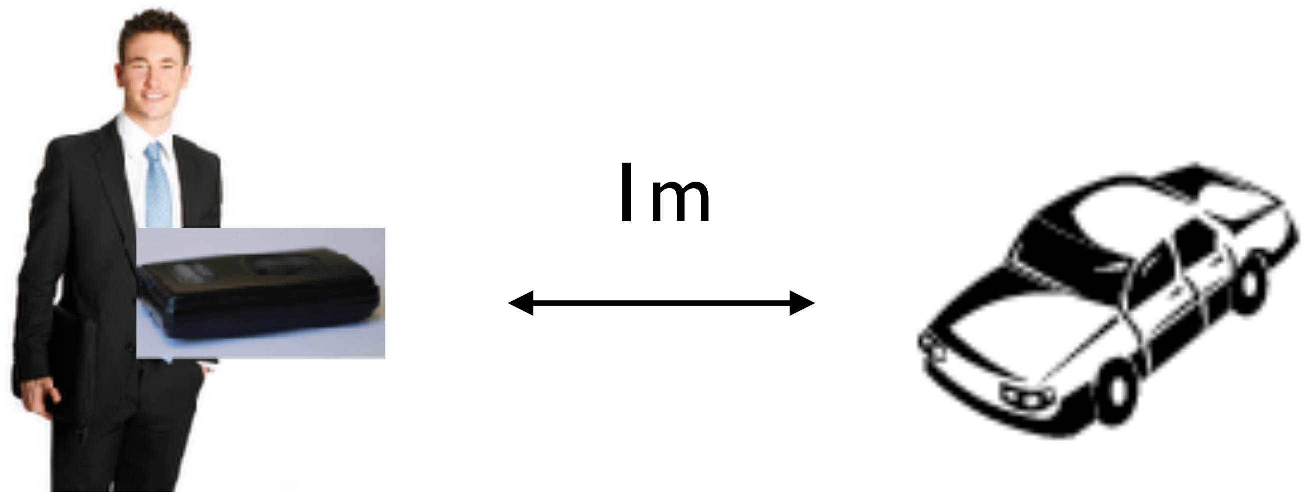
One (untrusted) device wants to *prove to be close* to another device.

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

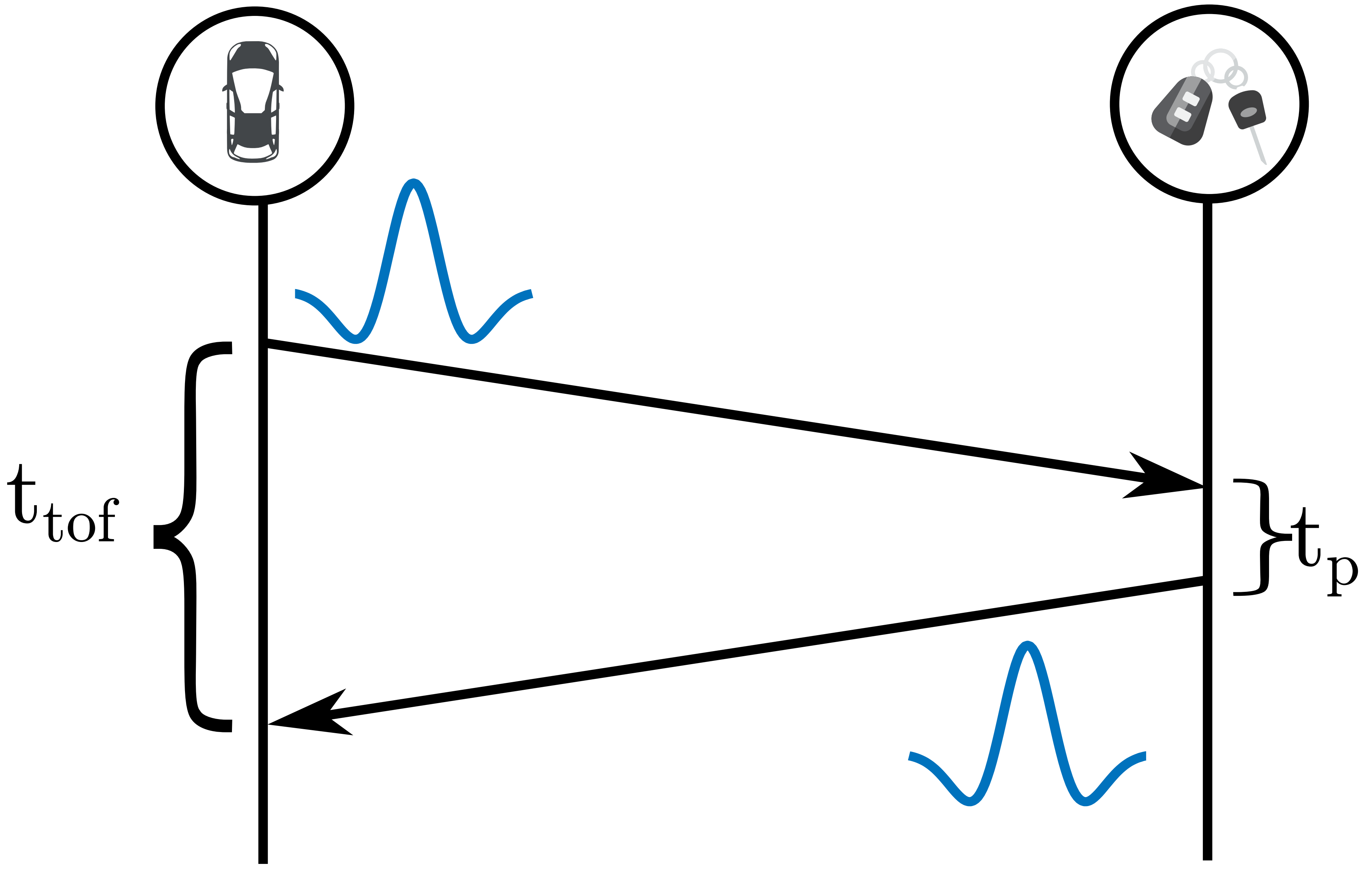


Two devices want to *verify if they are indeed close.*

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

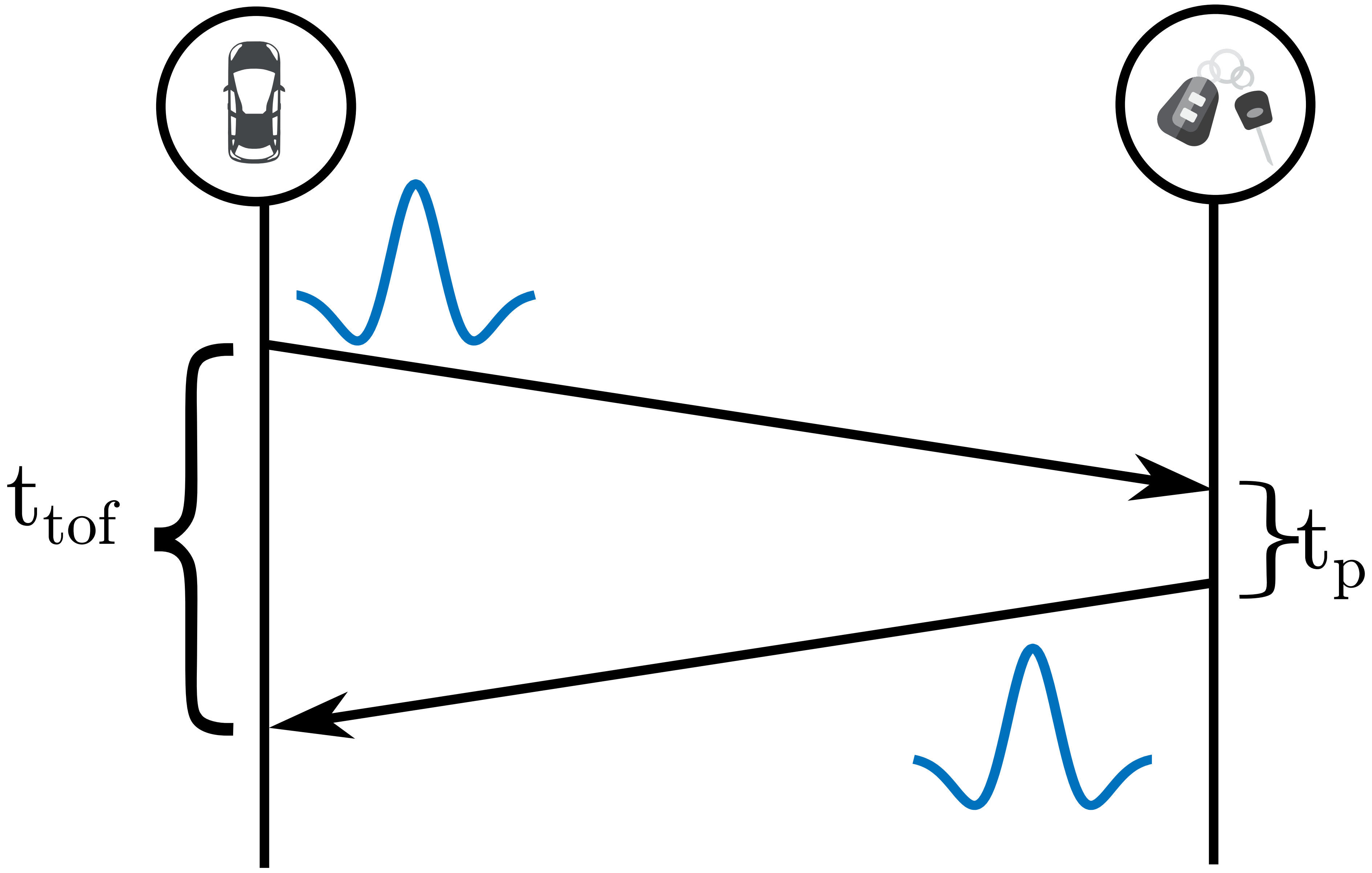


Estimating Proximity using Time of Flight



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

Estimating Proximity using Time of Flight



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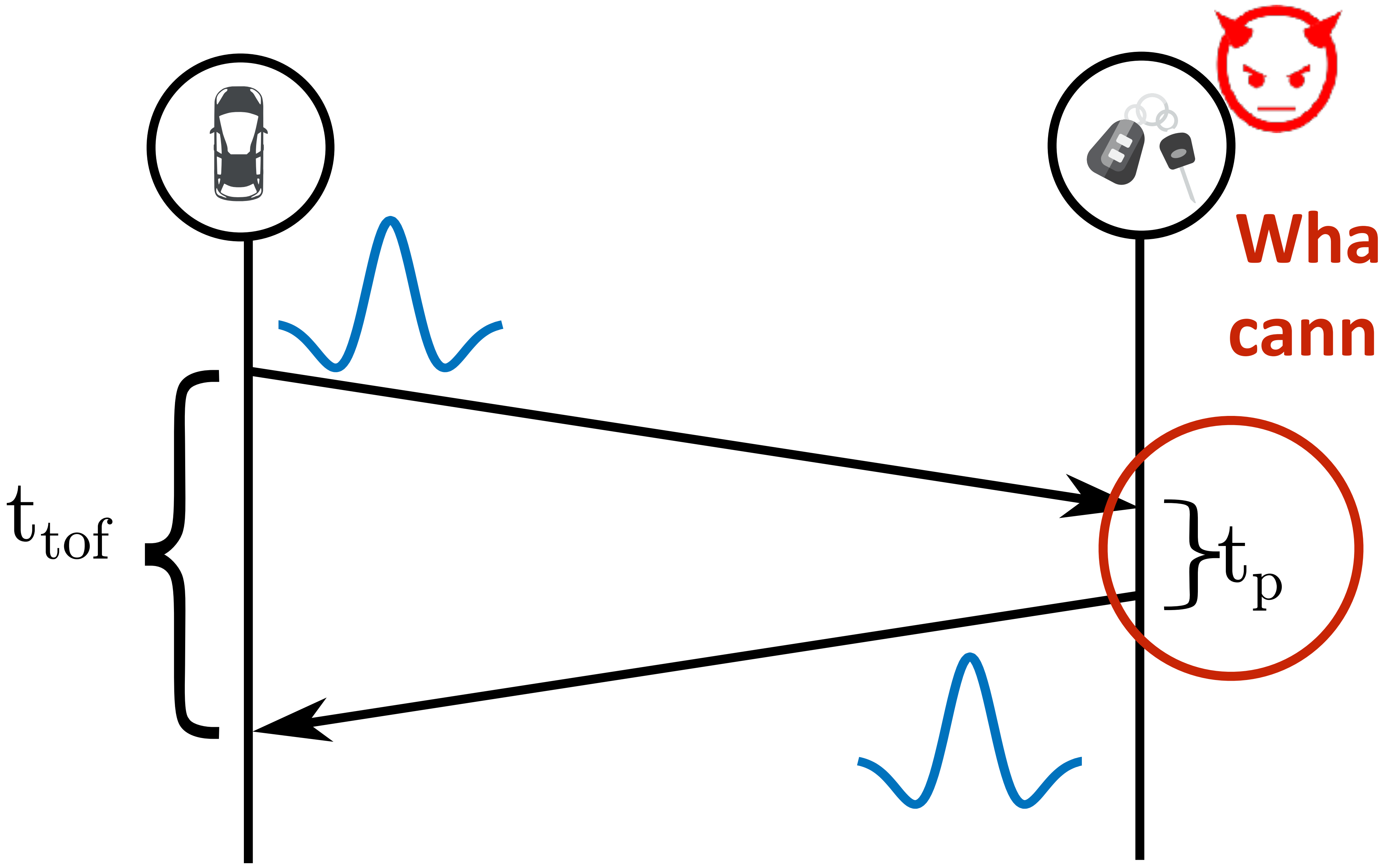
Can an attacker reduce time?

Manipulating time is harder than changing signal strength or phase

BUT…

Estimating Proximity using Time of Flight



What if the prover cannot be trusted?

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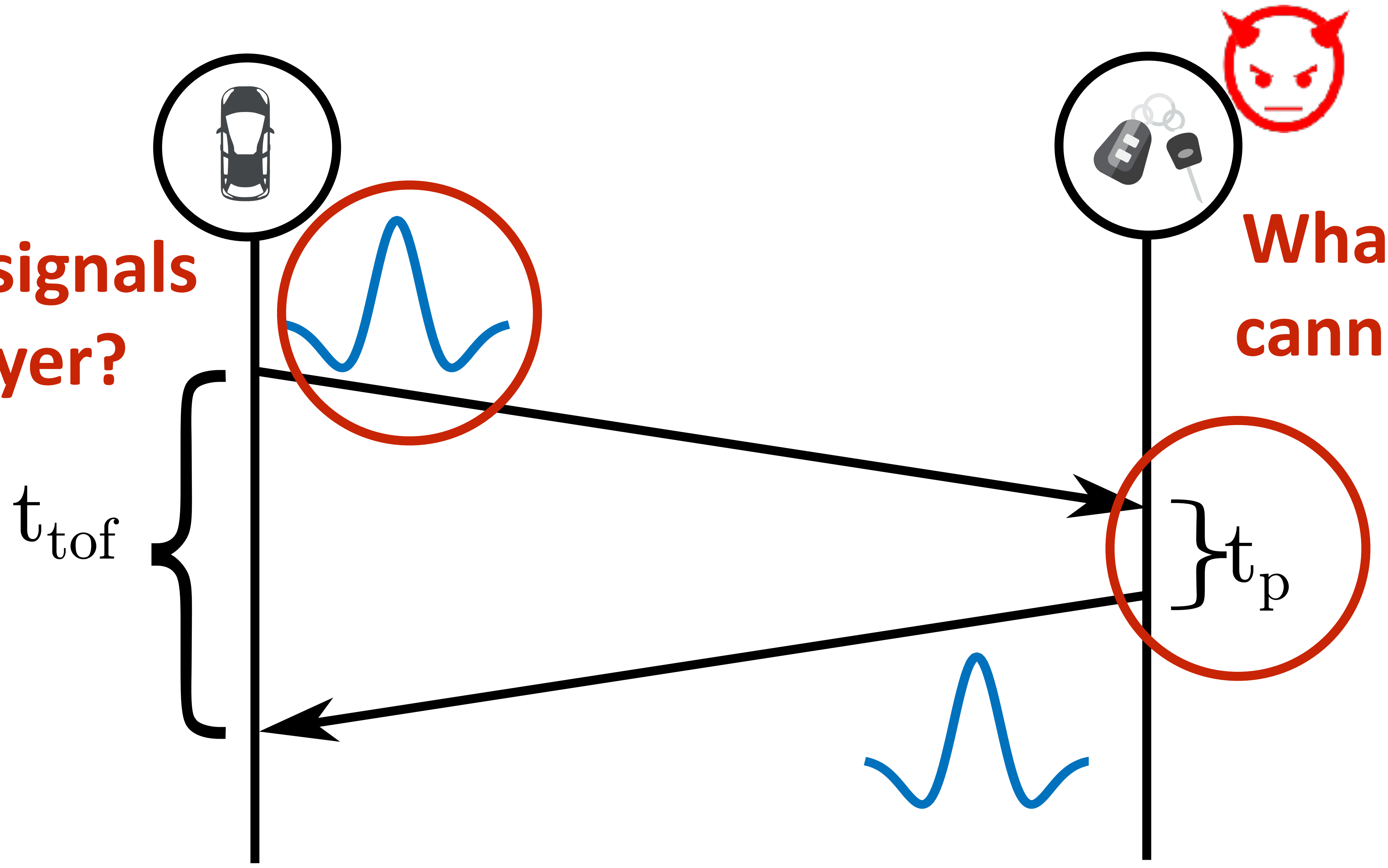


How to design the signals at the physical layer?

What if the prover cannot be trusted?

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

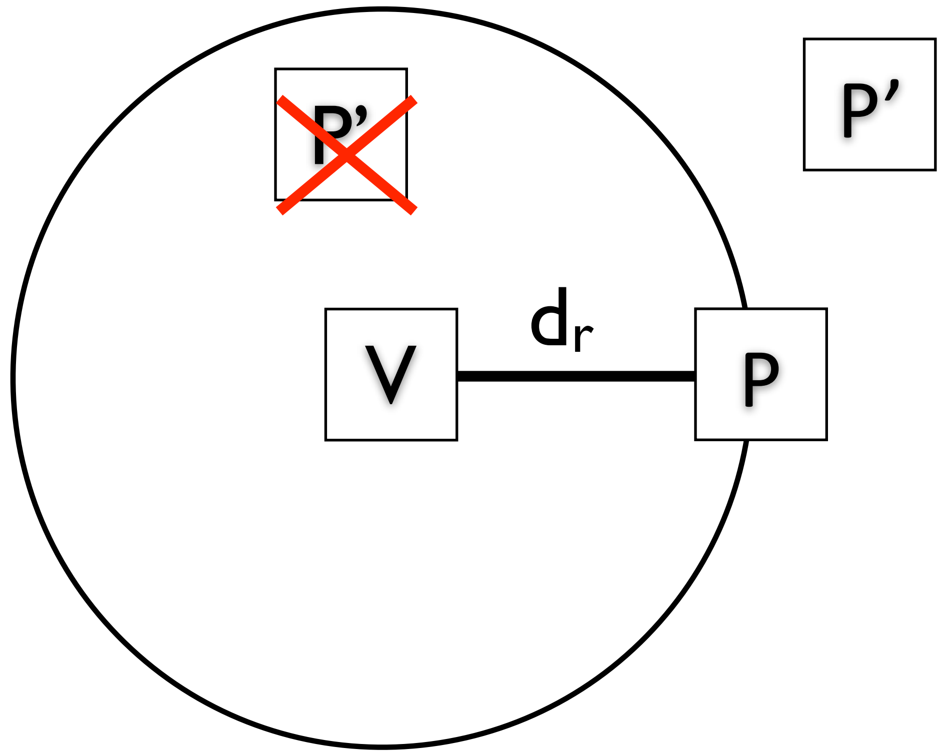
Can an attacker reduce time?

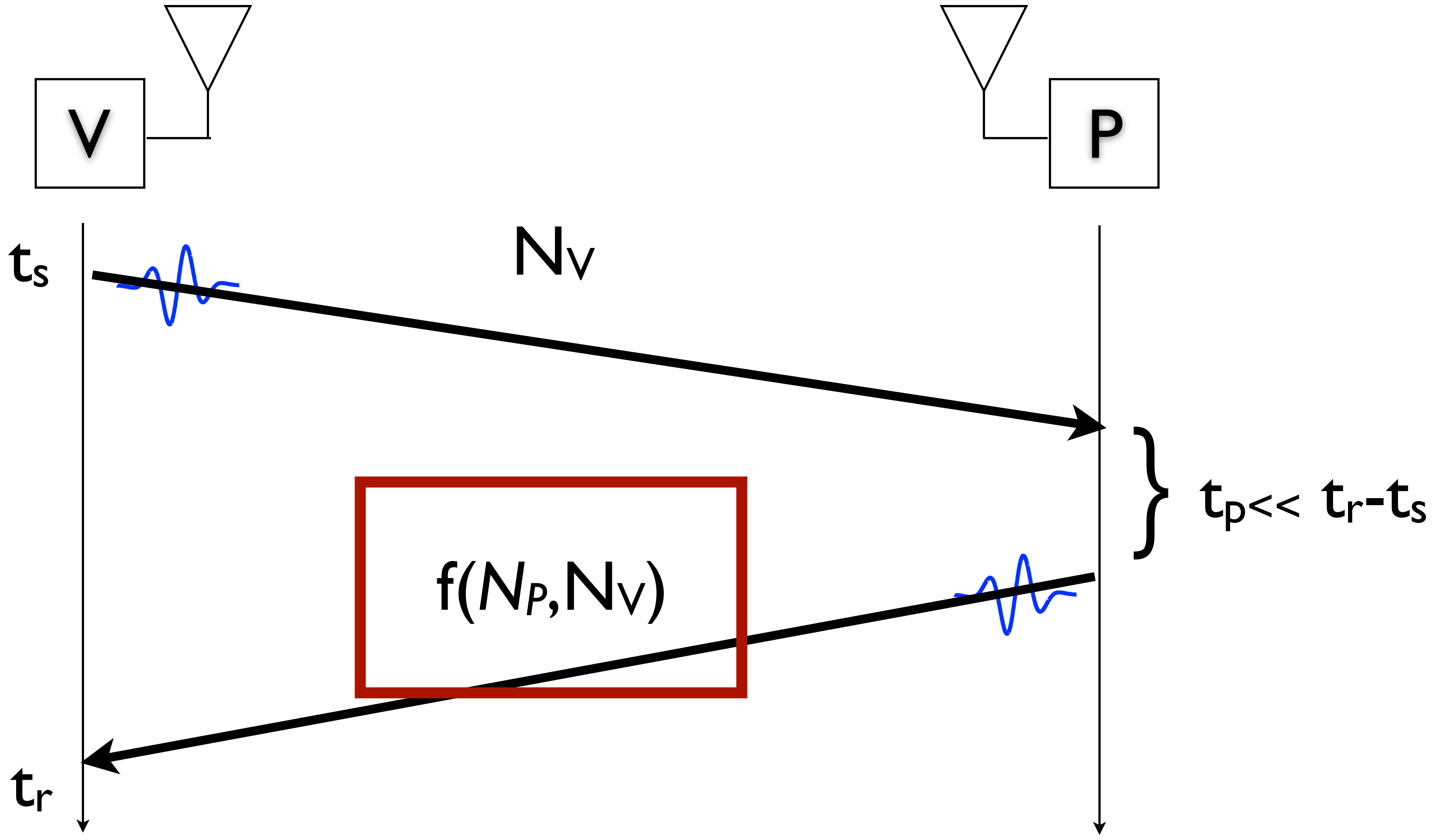
Manipulating time is harder than changing signal strength or phase

BUT…

Distance Bounding [BrandsChaum93]

Basic Idea



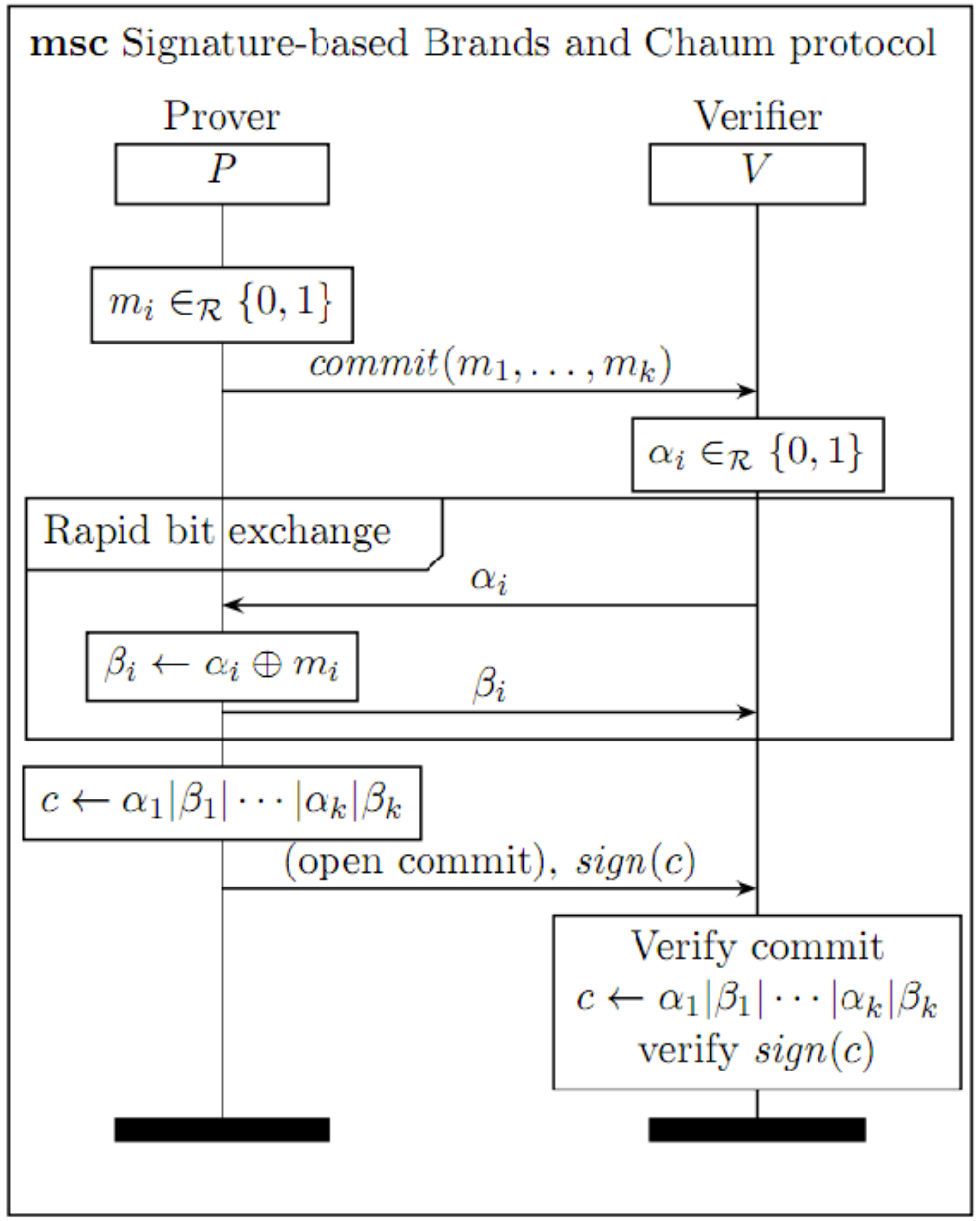


$d = (t_r - t_s - t_P)c/2$

Property:

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

Distance Bounding [BrandsChaum93]

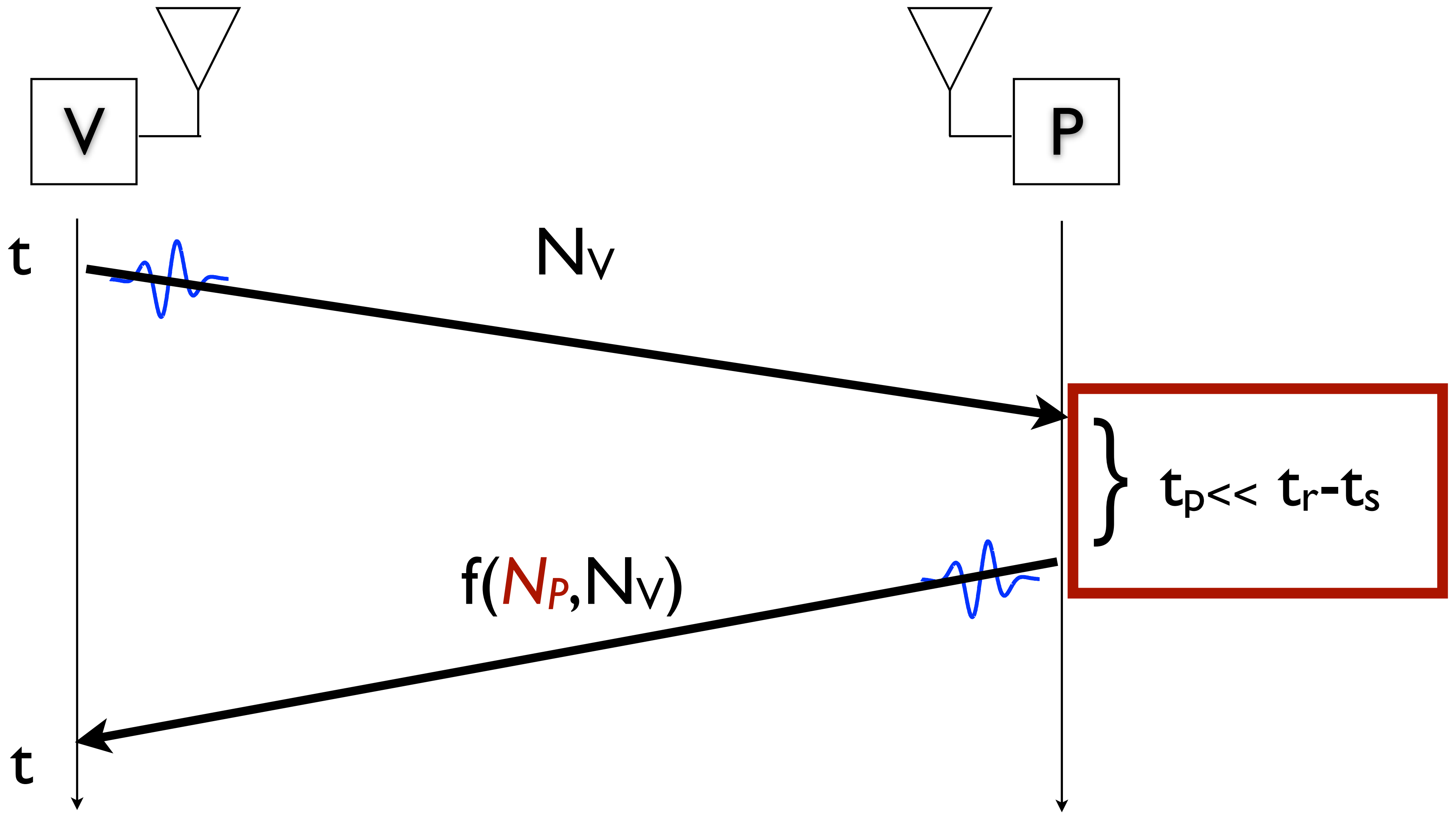


Distance Bounding: *f() and t_p*

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

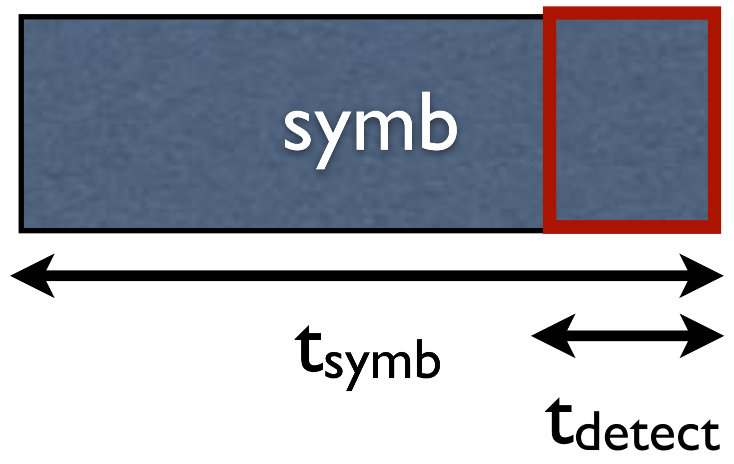


$d = (t_r - t_s - t_p)c/2$

Distance Bounding: *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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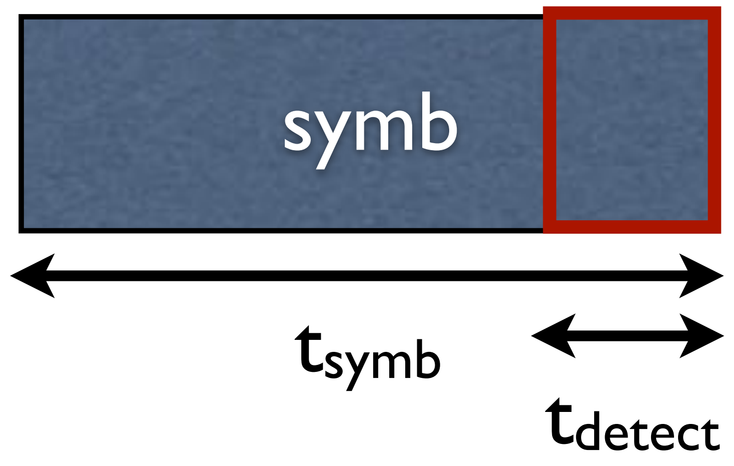


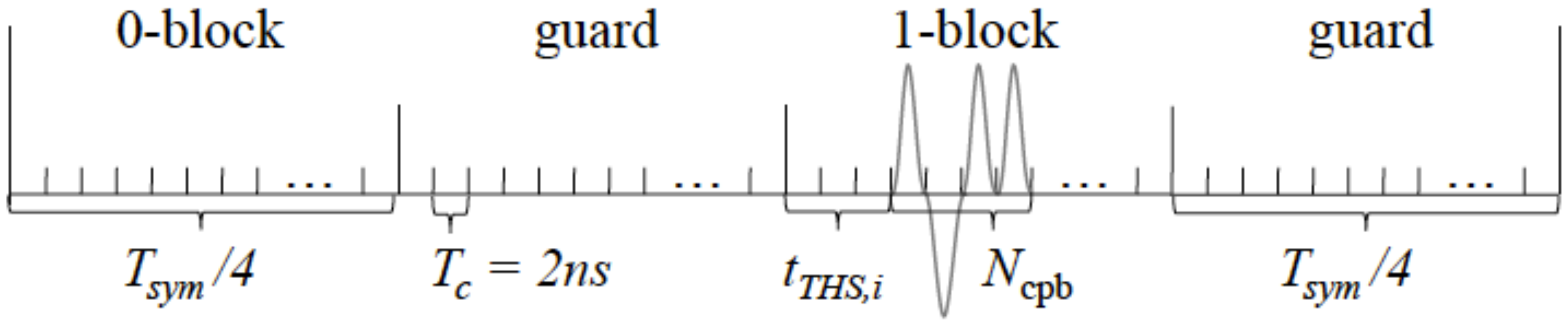
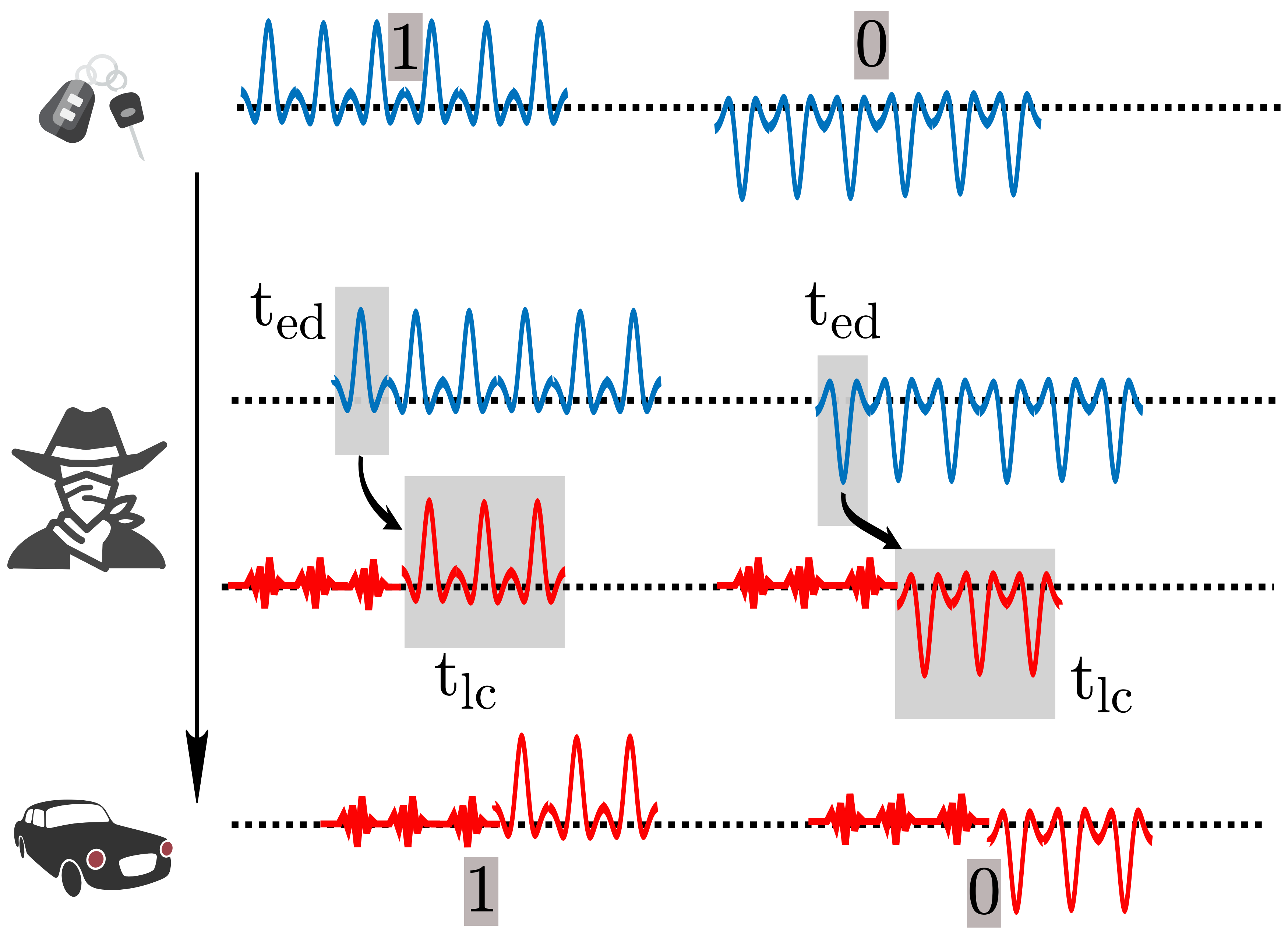


Figure 4.2: IEEE 802.15.4a data symbol structure [Poturalski2011]

Distance Bounding: *symbols*

Early detect and late commit attacks

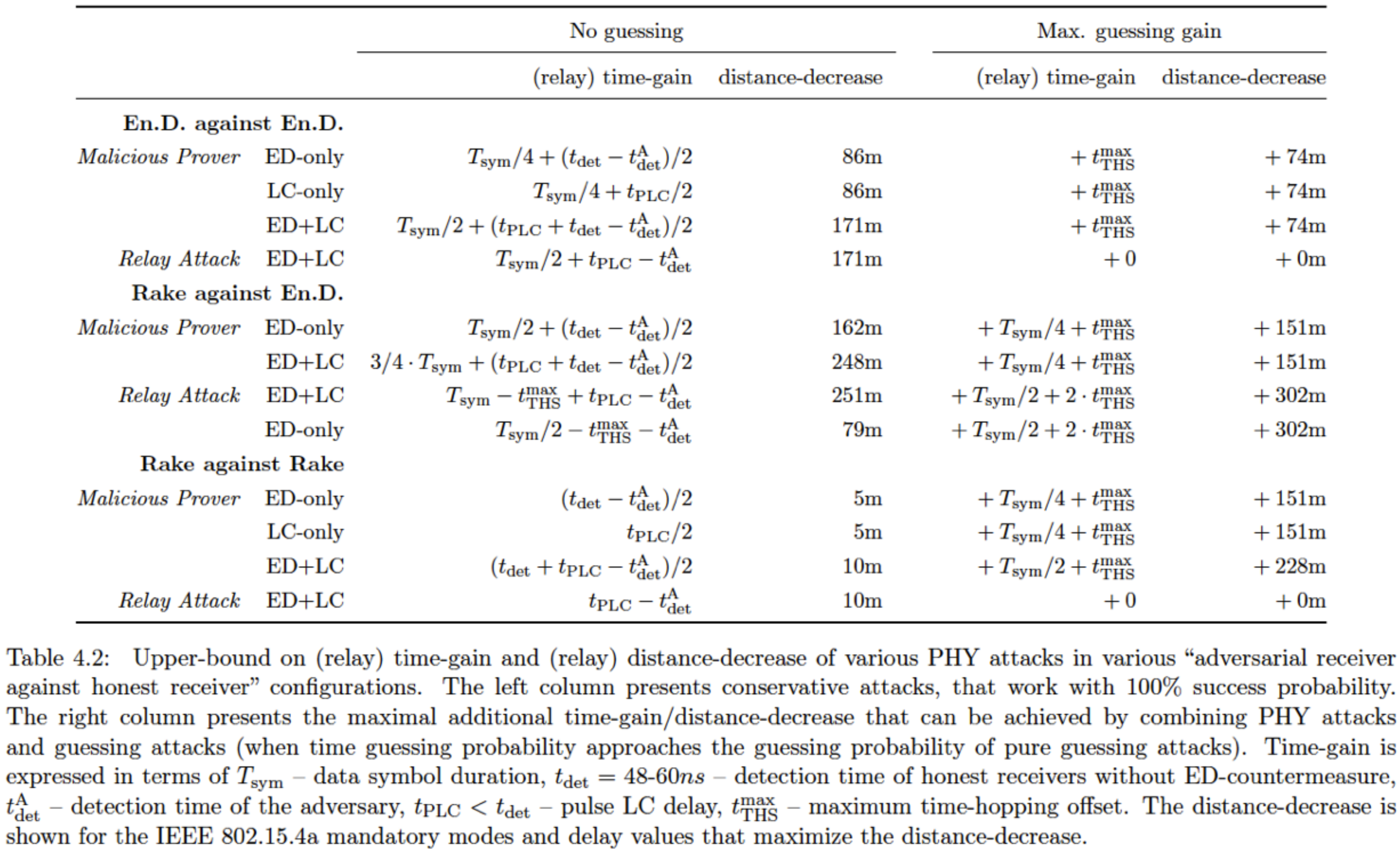


- Predicting the bit even before **completely** receiving it.
- Detecting a bit ‘1’ and ‘0’ from partially received symbols
- Transmit arbitrary signal until the symbol is **early detected**. Leverage receiver robustness.
- Short symbol length?

Distance Bounding

experiments on 802.15.4a (IR UWB)

[Poturalski2011]



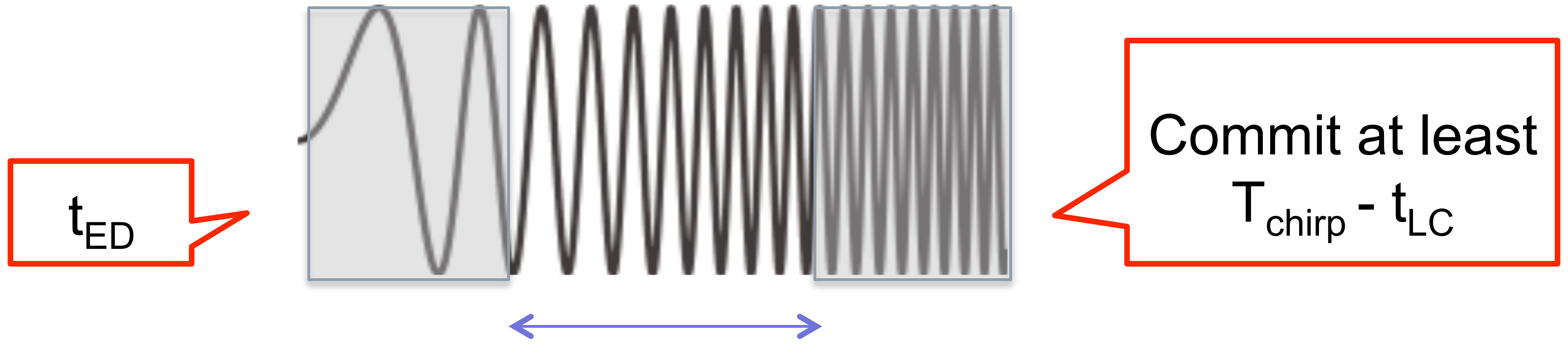
		No guessing		Max. guessing gain	
		(relay) time-gain	distance-decrease	(relay) time-gain	distance-decrease
En.D. against En.D.					
Malicious Prover	ED-only	$T_{\mathrm{sym}}/4 + (t_{\mathrm{det}} - t^{\mathrm{A}}_{\mathrm{det}})/2$	86m	$+\,t^{\max}_{\mathrm{THS}}$	$+\,74$m
	LC-only	$T_{\mathrm{sym}}/4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

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, $t_{\mathrm{det}} = 48\text{-}60ns$ – detection time of honest receivers without ED-countermeasure, $t^{\mathrm{A}}_{\mathrm{det}}$ – detection time of the adversary, $t_{\mathrm{PLC}} < t_{\mathrm{det}}$ – pulse LC delay, $t^{\max}_{\mathrm{THS}}$ – 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)

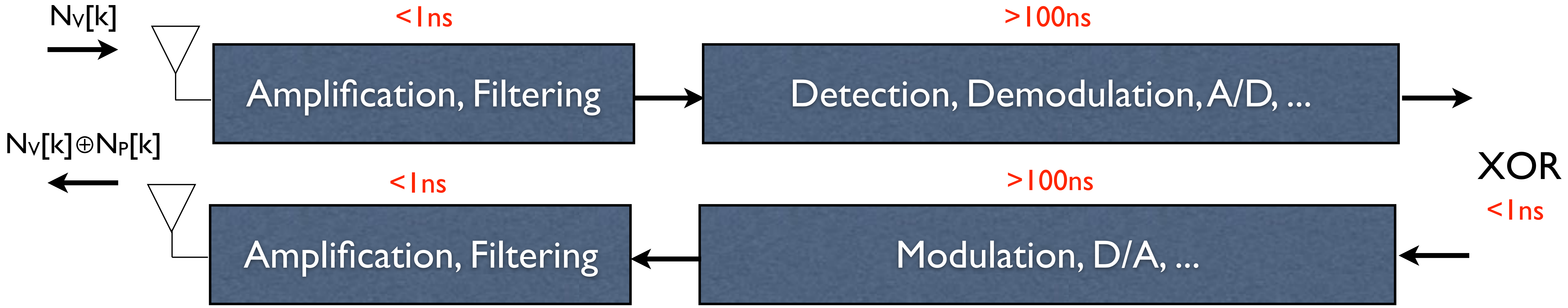
[BethDesmedt] sign(); h(); mac(); E(); … => $t_p >> ns$

[**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 don't require interpretation (demodulation) Nv ?

Realization of RF Distance Bounding:

Processing Function $f(N_v,N_p)$

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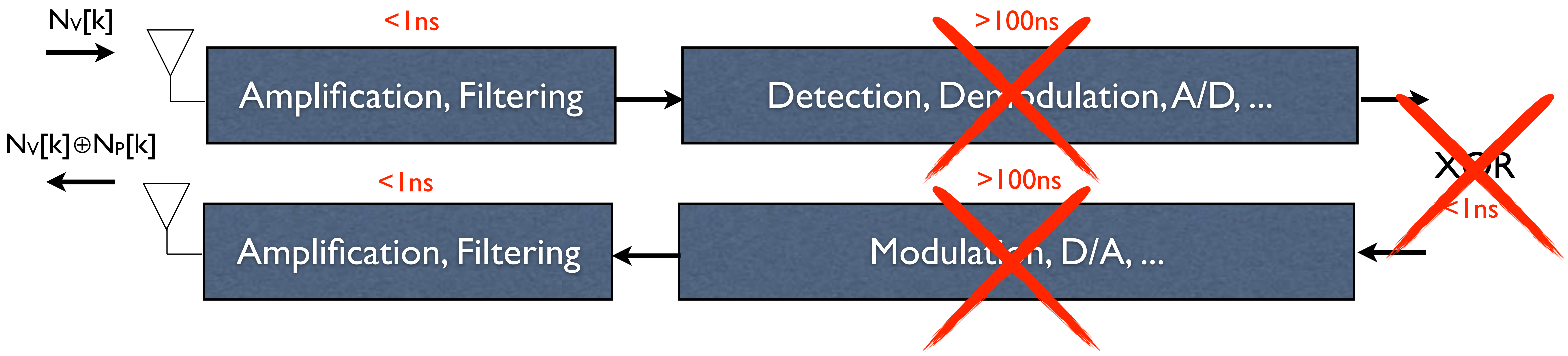


$N_V[k]$

$N_V[k] \oplus N_P[k]$

<1ns

Amplification, Filtering

~~>100ns~~

~~Detection, Demodulation, A/D, …~~

~~XOR~~

~~<1ns~~

<1ns

Amplification, Filtering

~~>100ns~~

~~Modulation, D/A, …~~

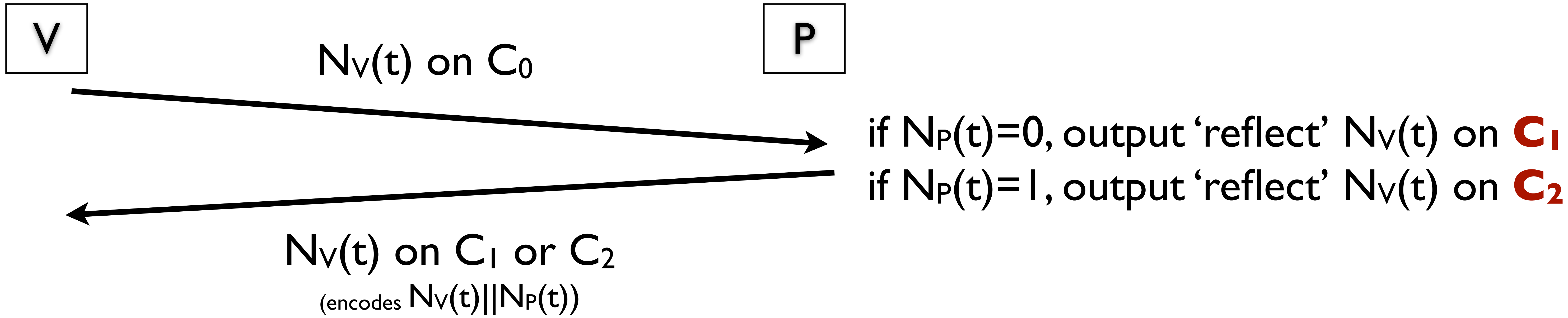
Can we use functions that don't require interpretation (demodulation) Nv ?

A new Function: CRCS

This 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)



V

P

$N_V(t)$ on C_0

if $N_P(t)=0$, output 'reflect' $N_V(t)$ on **C_1**

if $N_P(t)=1$, output 'reflect' $N_V(t)$ on **C_2**

$N_V(t)$ on C_1 or C_2

(encodes $N_V(t)||N_P(t)$)

A new Function: CRCS

This 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)

A new Function: CRCS

This approach: *Challenge Reflection with Channel Selection*

- Prover does not interpret Nv
- All *time-critical* processing is done in *analog*
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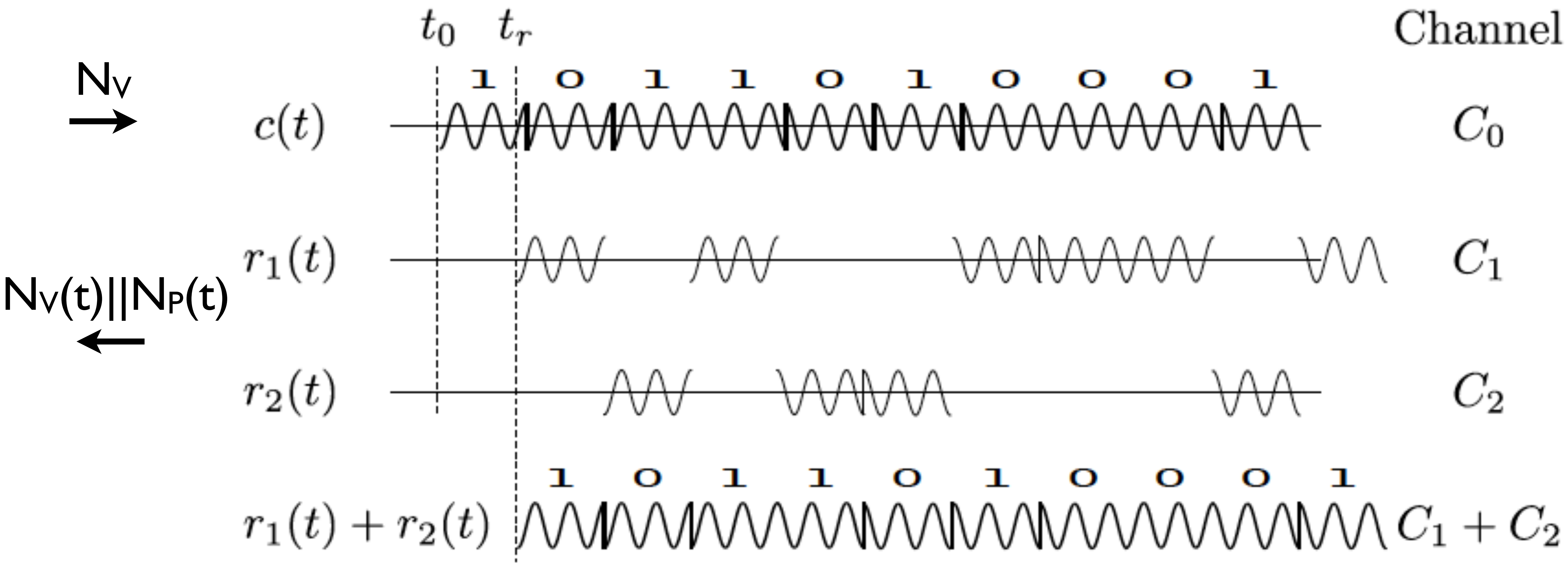
Main idea (C_0,C_1,C_2 are channels)

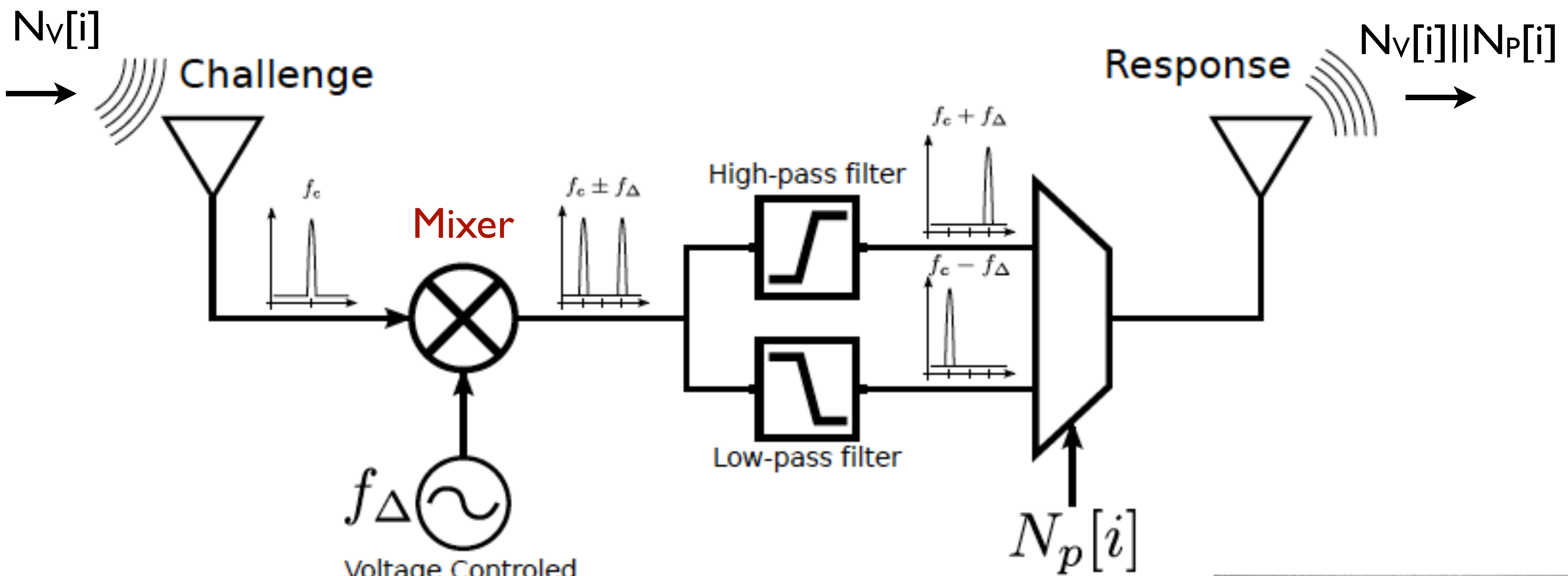


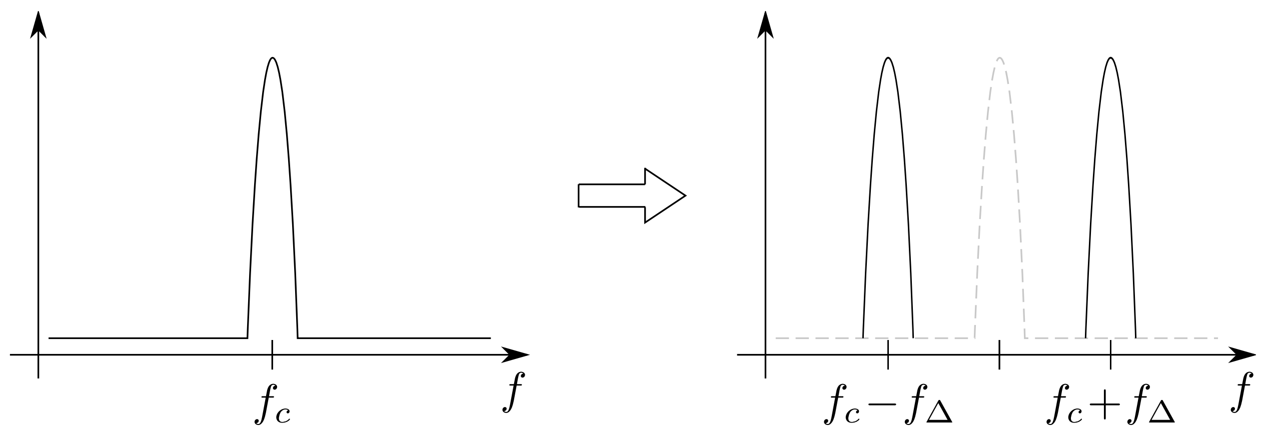
N_V →

$N_V(t)||N_P(t)$ ←

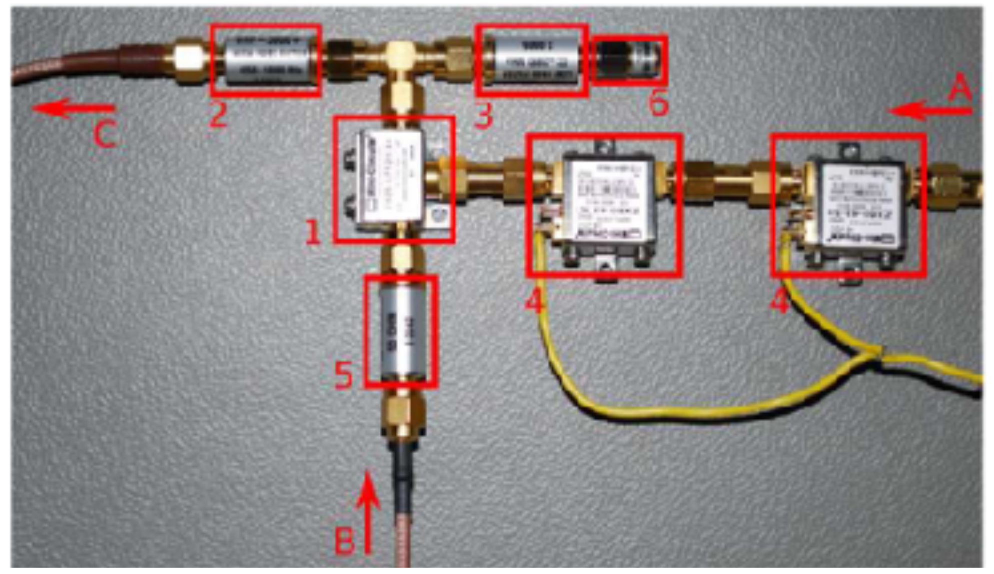
A new Function: CRCS

Implementation of CRCS





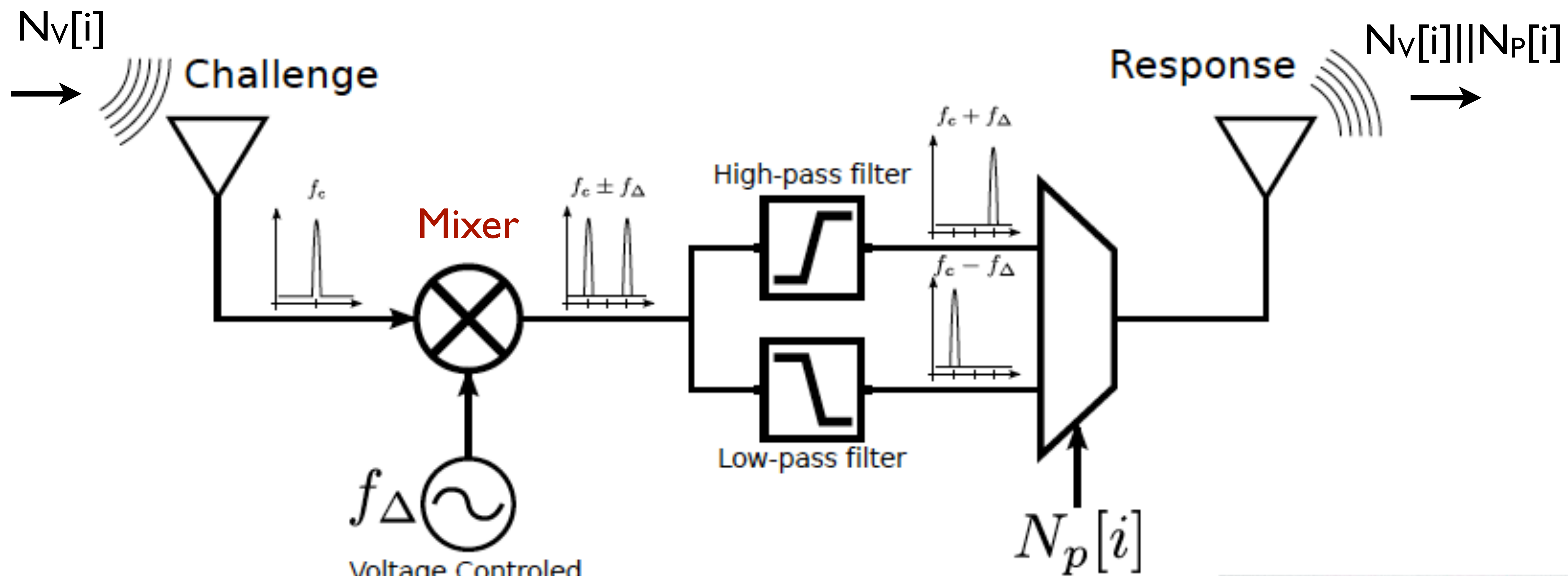
Mixer up+down converts the input signal

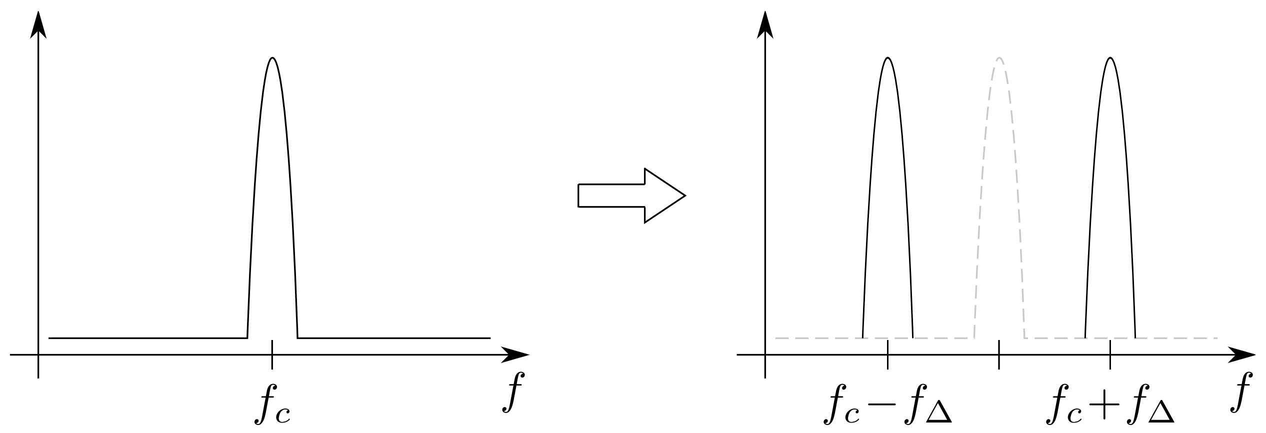


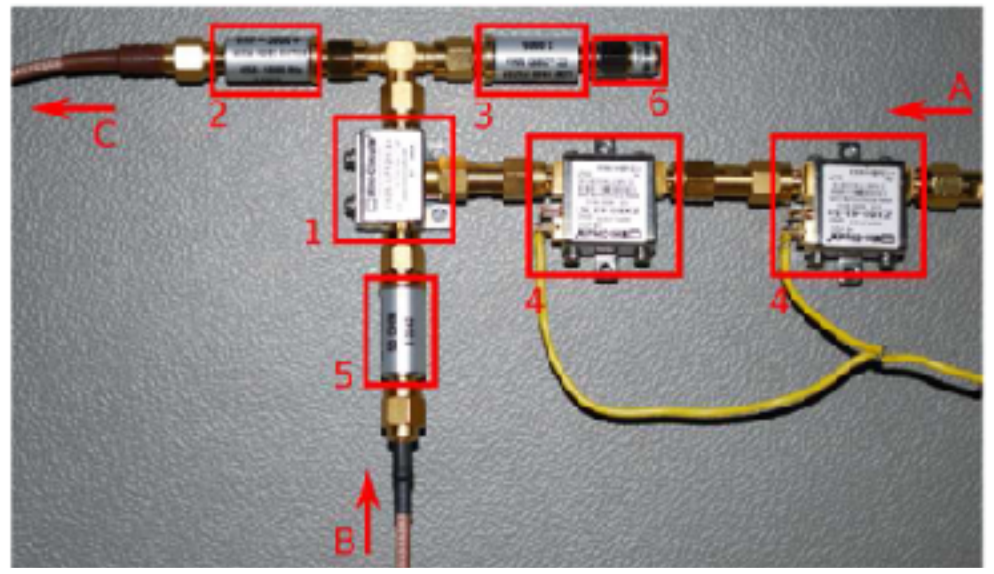
A new Function: CRCS

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)

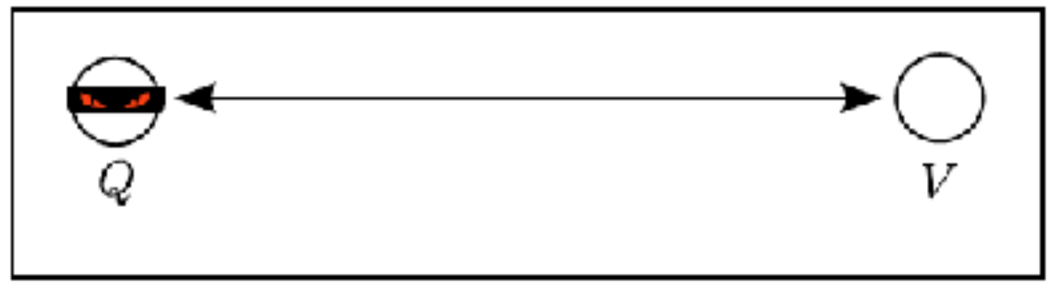
```
Acquisition is stopped.
40.0 GSa/s   400 kpts
```

```
Source       Vertical Scale  Offset     Horizontal Scale  Position
Channel 1    100 mV/div      -164.0 mV  1.00 ns/div       -1.6757226 µs
Channel 2    20.0 mV/div     35.0 mV    1.00 ns/div       -1.6757226 µs
```

Two basic Attacks on DB protocols

Distance Fraud

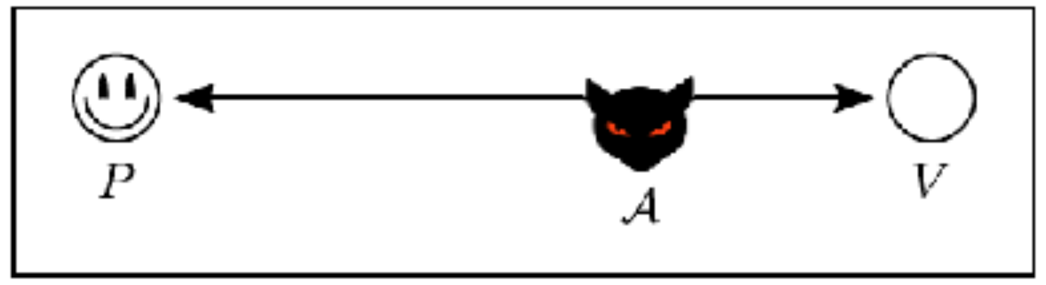
- dishonest prover pretends to be closer to the verifier
- “pacemaker scenario”



Distance Fraud

Mafia Fraud

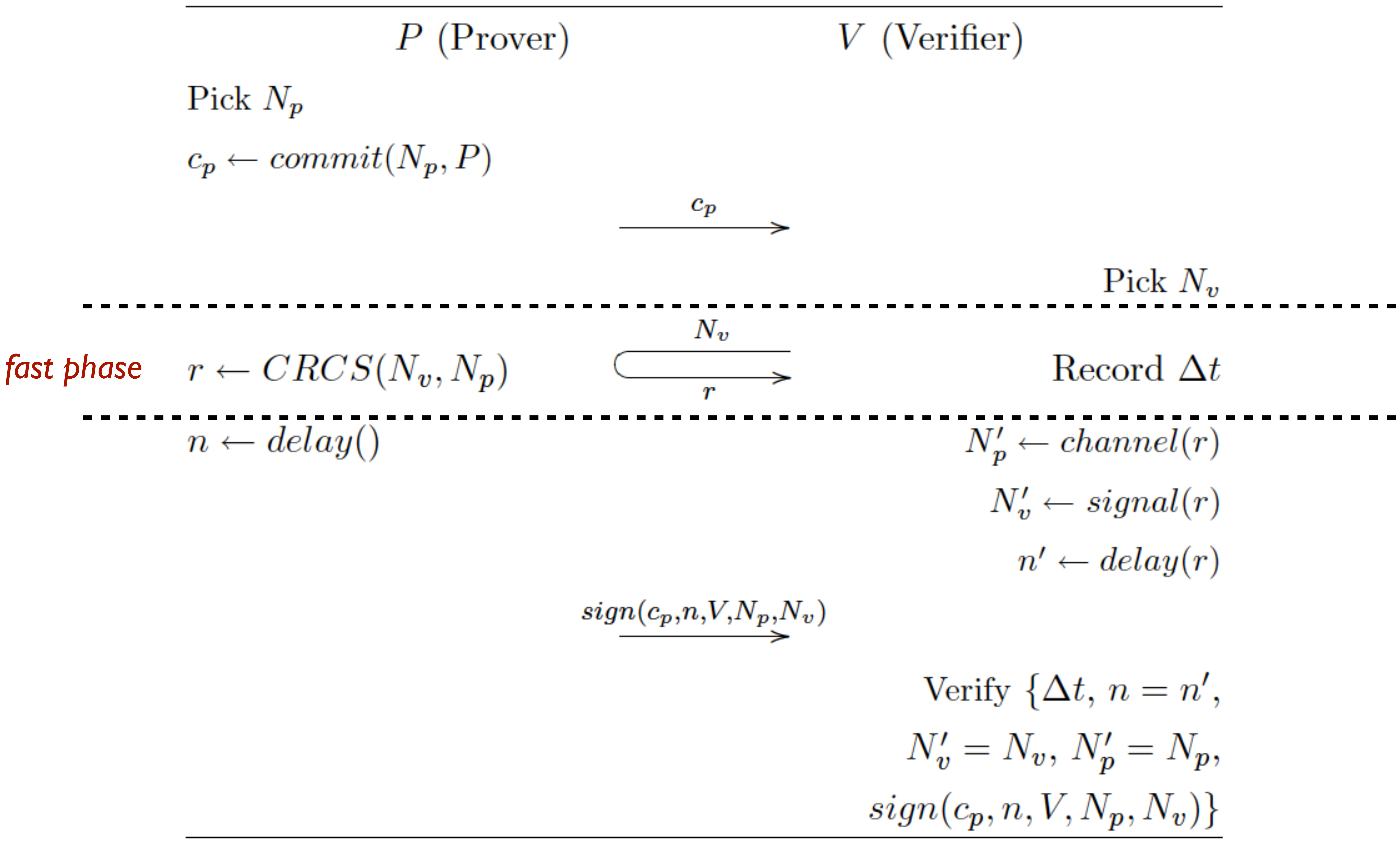
- honest prover
- attacker convinces verifier and prover that they are closer
- relay attack (“car and key scenario)



Mafia Fraud

CRCS

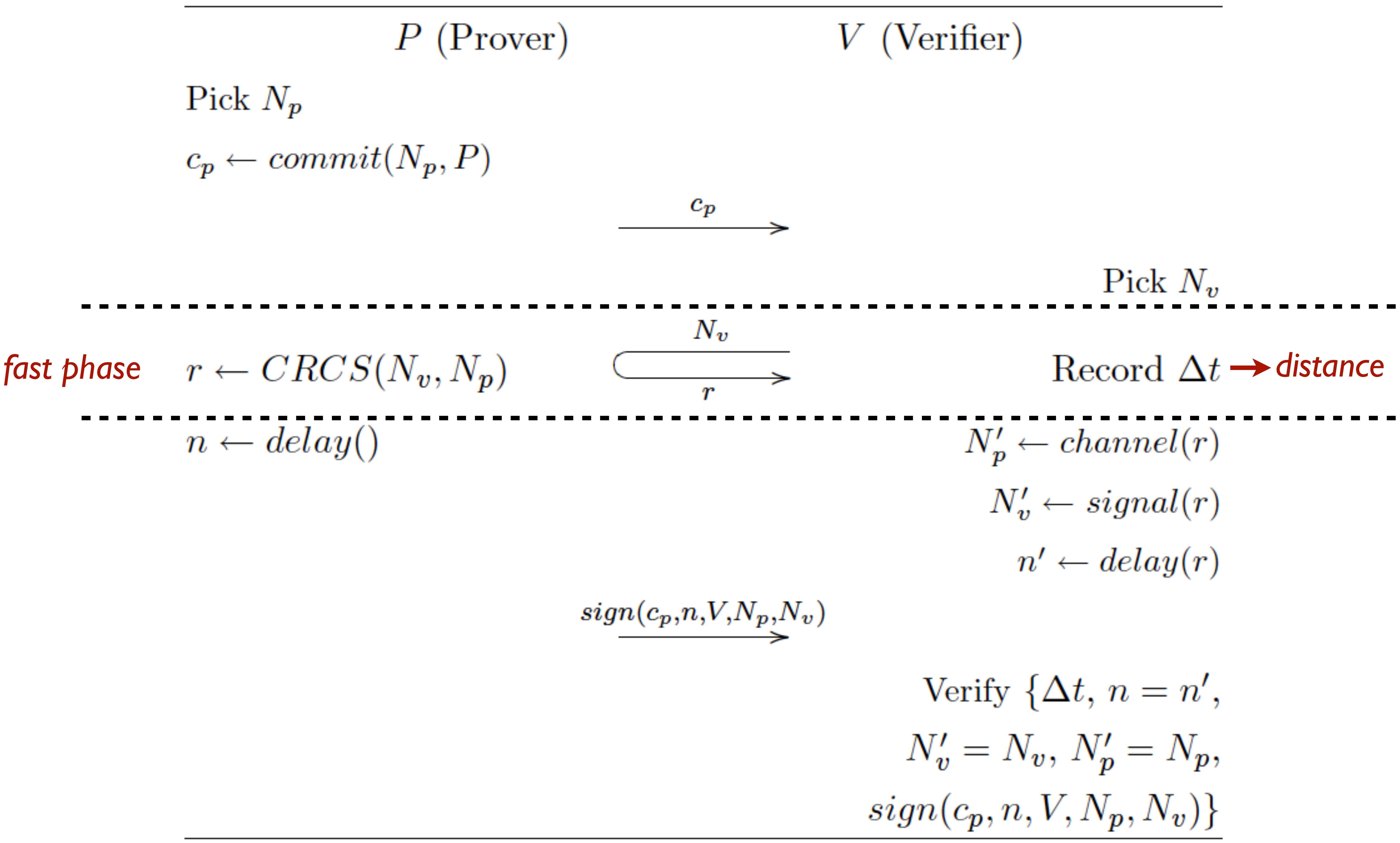
CRCS-based DB protocol *(vs Distance and Mafia Fraud)*



	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 Δt
	$n \leftarrow delay()$		$N'_p \leftarrow channel(r)$
			$N'_v \leftarrow signal(r)$
			$n' \leftarrow delay(r)$
		$\xrightarrow{sign(c_p,n,V,N_p,N_v)}$	
			Verify $\{\Delta t,\ n = n',$ $N'_v = N_v,\ N'_p = N_p,$ $sign(c_p, n, V, N_p, N_v)\}$

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 Δt → *distance*

$n \leftarrow delay()$

$N'_p \leftarrow channel(r)$

$N'_v \leftarrow signal(r)$

$n' \leftarrow delay(r)$

$\xrightarrow{sign(c_p,n,V,N_p,N_v)}$

Verify $\{\Delta t,\ n = n',$

$N'_v = N_v,\ N'_p = N_p,$

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CRCS

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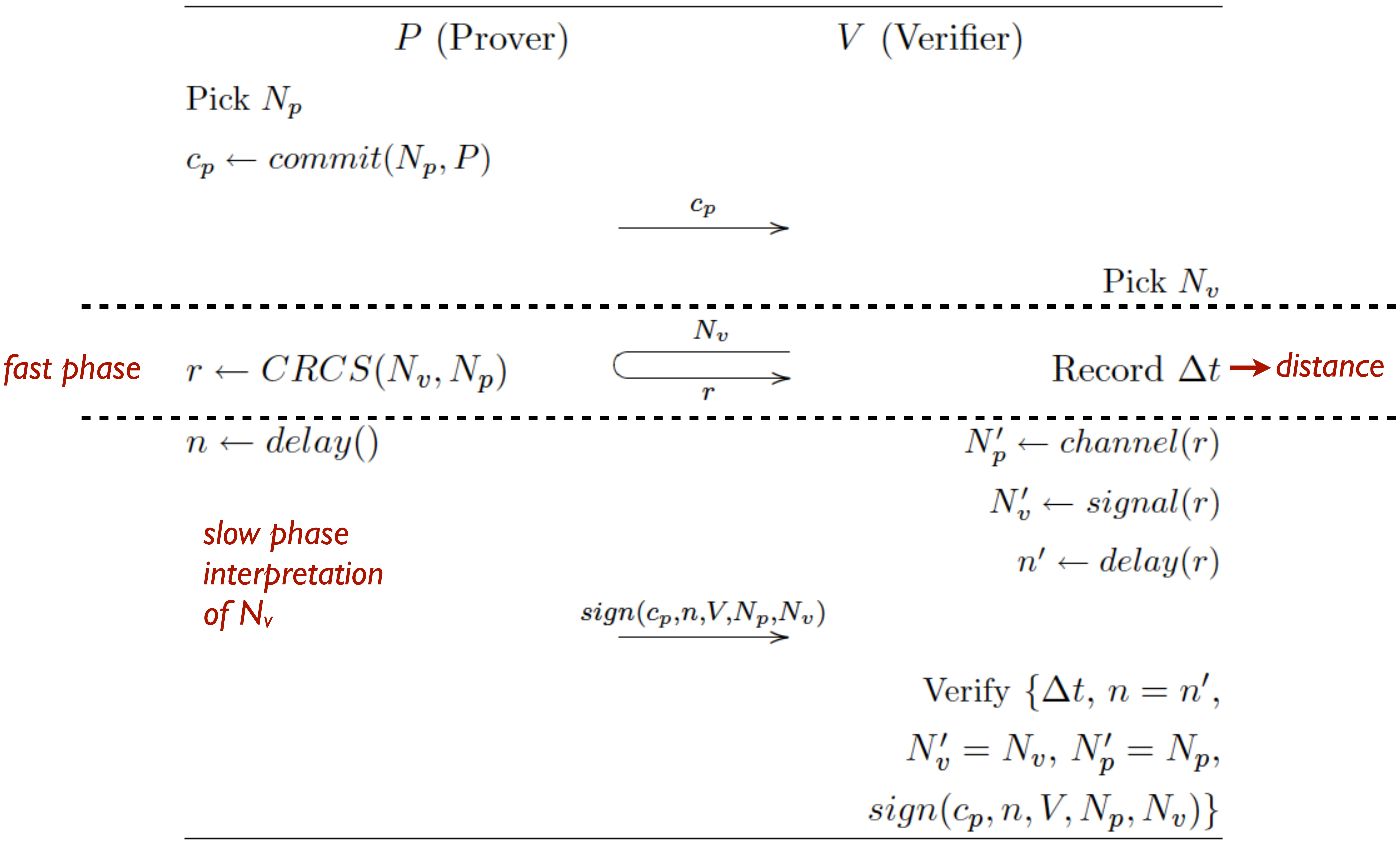

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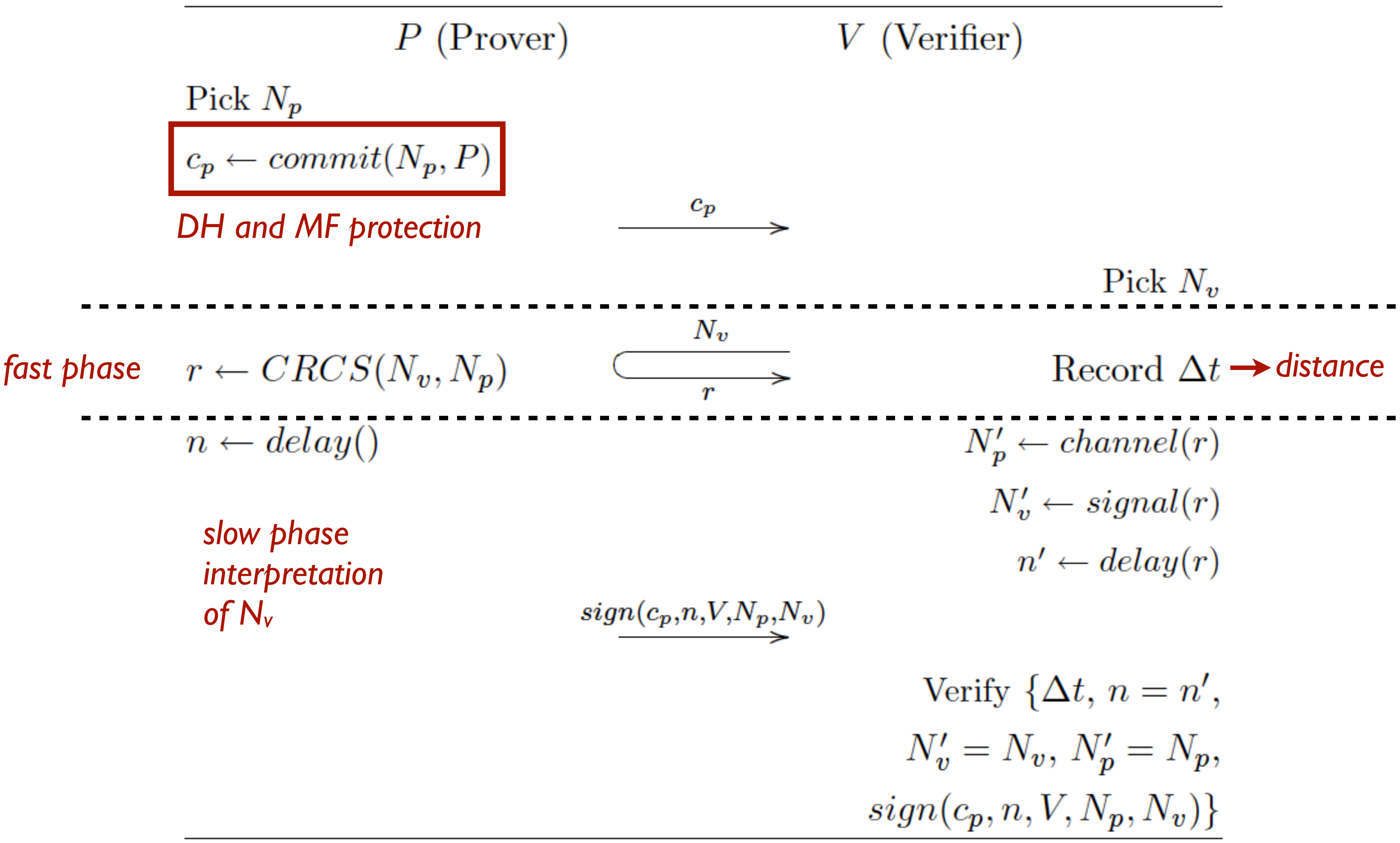
$c_p \leftarrow commit(N_p, P)$		
	$\xrightarrow{c_p}$	
		Pick N_v
fast phase $r \leftarrow CRCS(N_v, N_p)$	N_v / r	Record Δt → *distance*
$n \leftarrow delay()$		$N_p' \leftarrow channel(r)$
		$N_v' \leftarrow signal(r)$
slow phase interpretation of N_v		$n' \leftarrow delay(r)$
	$\xrightarrow{sign(c_p,n,V,N_p,N_v)}$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

CRCS

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



P (Prover)

V (Verifier)

Pick N_p

$\boxed{c_p \leftarrow commit(N_p, P)}$

DH and MF protection

$\xrightarrow{c_p}$

Pick N_v

fast phase

$r \leftarrow CRCS(N_v, N_p)$

N_v

r

Record Δt → distance

$n \leftarrow delay()$

$N'_p \leftarrow channel(r)$

$N'_v \leftarrow signal(r)$

$n' \leftarrow delay(r)$

slow phase
interpretation
of N_v

$\xrightarrow{sign(c_p, n, V, N_p, N_v)}$

Verify $\{\Delta t,\ n = n',$

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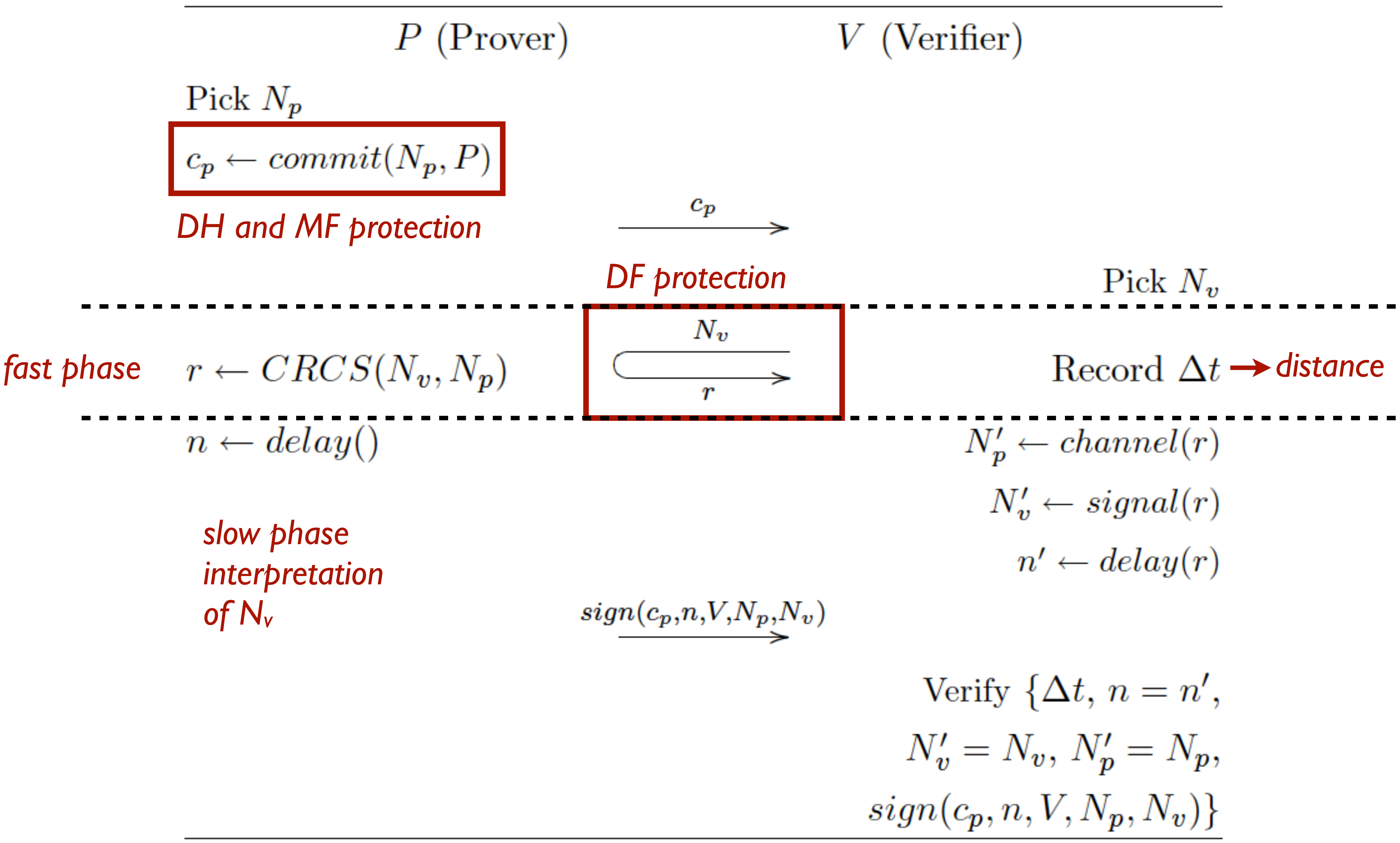
CRCS

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



P (Prover) V (Verifier)

Pick N_p

$\boxed{c_p \leftarrow commit(N_p, P)}$

DH and MF protection

$\xrightarrow{c_p}$

DF protection

Pick N_v

fast phase

$r \leftarrow CRCS(N_v, N_p)$

N_v, r

Record Δt → distance

$n \leftarrow delay()$

$N'_p \leftarrow channel(r)$

$N'_v \leftarrow signal(r)$

$n' \leftarrow delay(r)$

slow phase
interpretation
of N_v

$\xrightarrow{sign(c_p, n, V, N_p, N_v)}$

Verify $\{\Delta t,\ n = n',$

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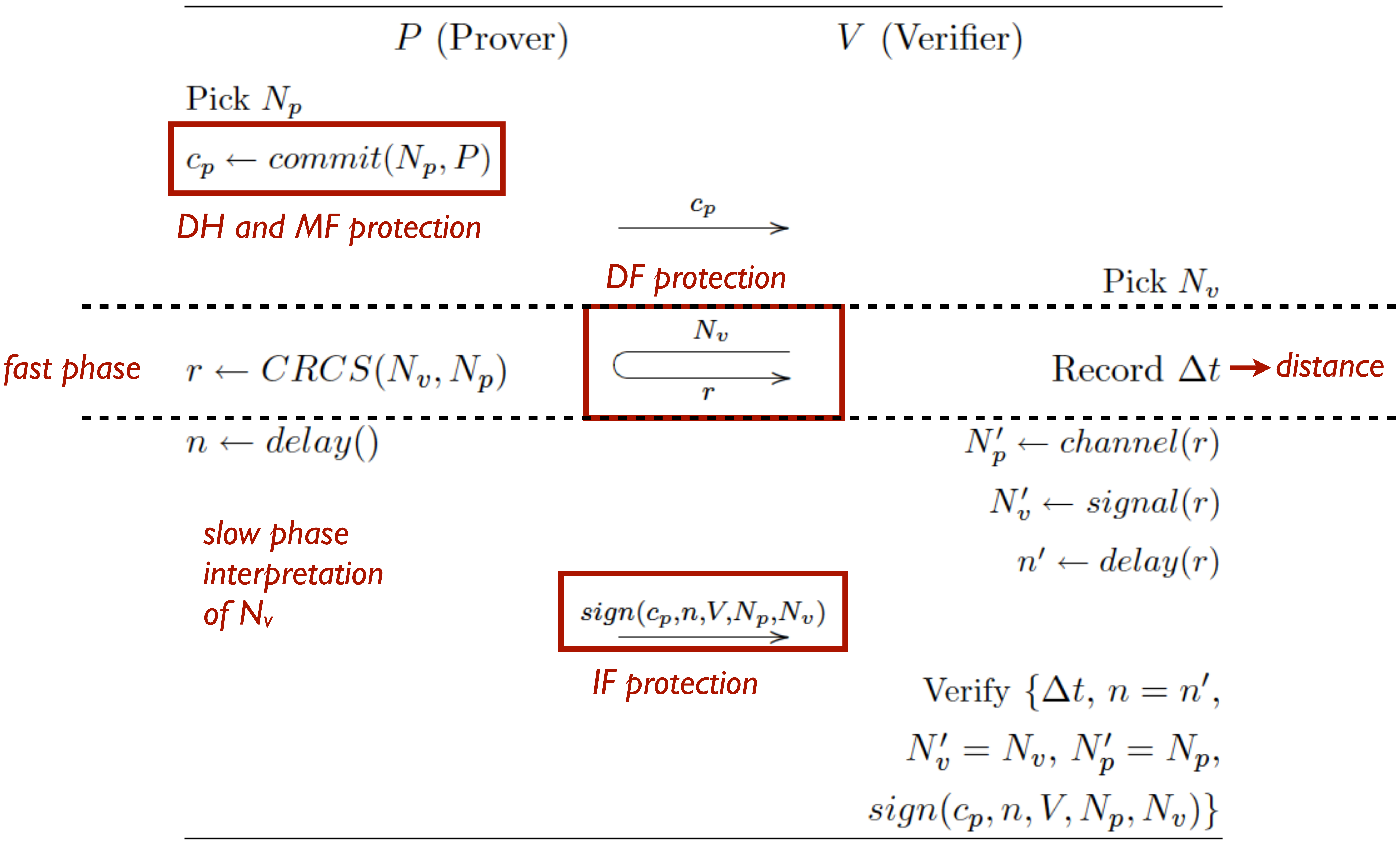
CRCS

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



P (Prover) V (Verifier)

Pick N_p

$\boxed{c_p \leftarrow commit(N_p, P)}$

DH and MF protection

$\xrightarrow{c_p}$

DF protection

Pick N_v

fast phase $r \leftarrow CRCS(N_v, N_p)$ $\xrightarrow{N_v}$ $\xrightarrow{r}$ Record Δt → *distance*

$n \leftarrow delay()$

$N'_p \leftarrow channel(r)$

$N'_v \leftarrow signal(r)$

$n' \leftarrow delay(r)$

slow phase interpretation of N$_v$

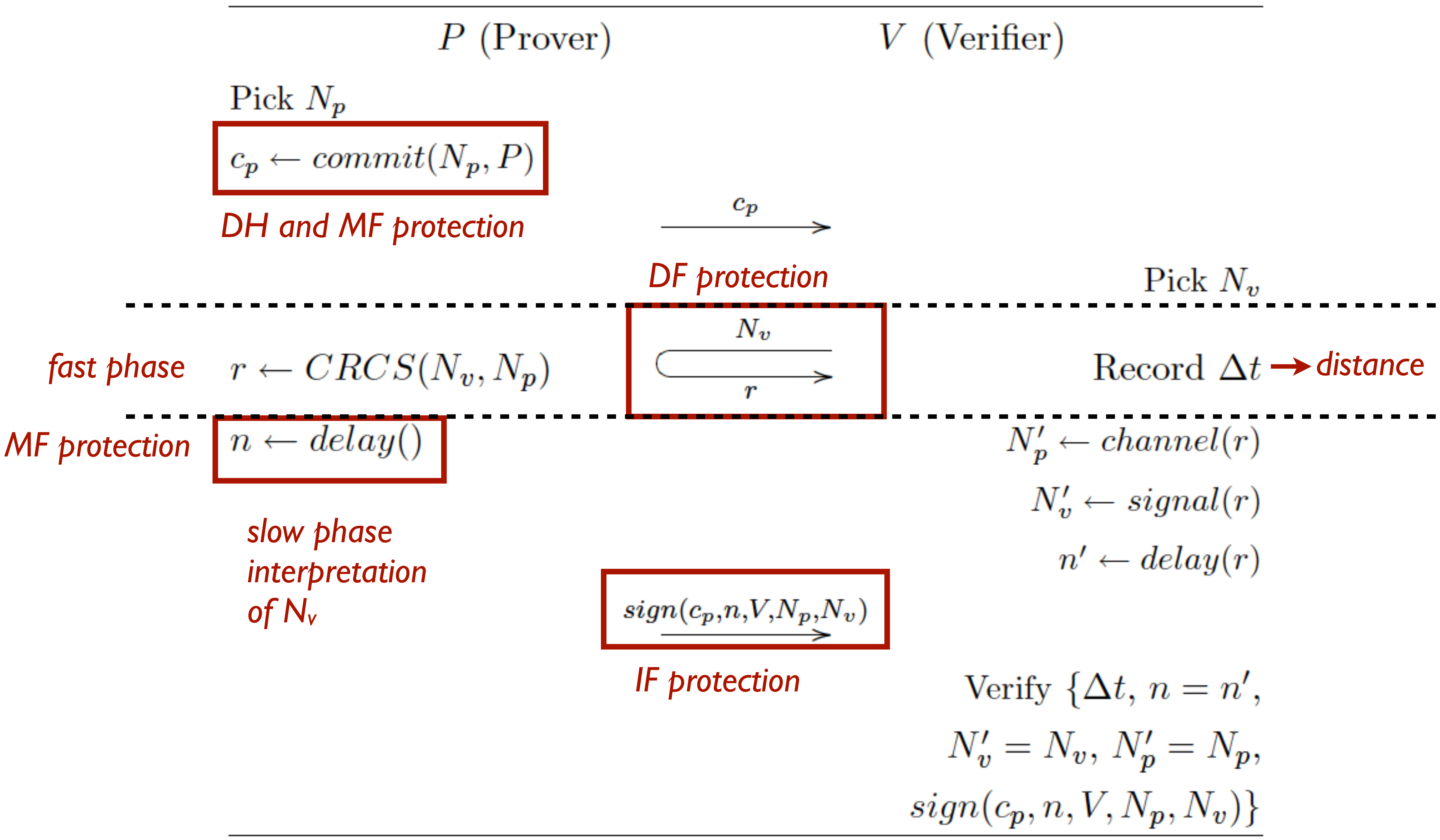
$\boxed{\xrightarrow{sign(c_p, n, V, N_p, N_v)}}$

IF protection

Verify $\{\Delta t,\ n = n',$
$N'_v = N_v,\ N'_p = N_p,$
$sign(c_p, n, V, N_p, N_v)\}$

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

$r \leftarrow CRCS(N_v, N_p)$

N_v

r

Record Δt → distance

MF protection

$n \leftarrow delay()$

$N'_p \leftarrow channel(r)$

$N'_v \leftarrow signal(r)$

$n' \leftarrow delay(r)$

slow phase
interpretation
of N_v

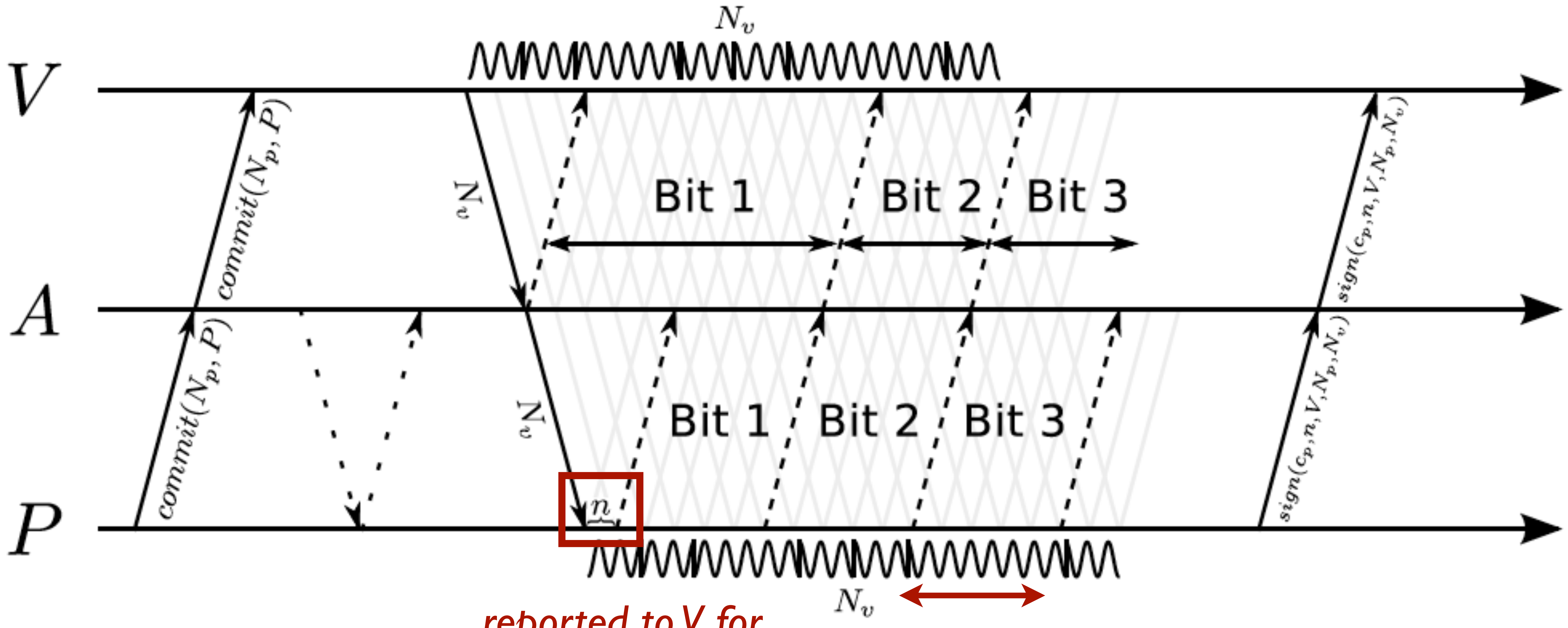
$\xrightarrow{sign(c_p,n,V,N_p,N_v)}$

IF protection

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

Mafia Fraud Detection *(physical layer)*



reported to V for MF protection

fixed bit width

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 (?)

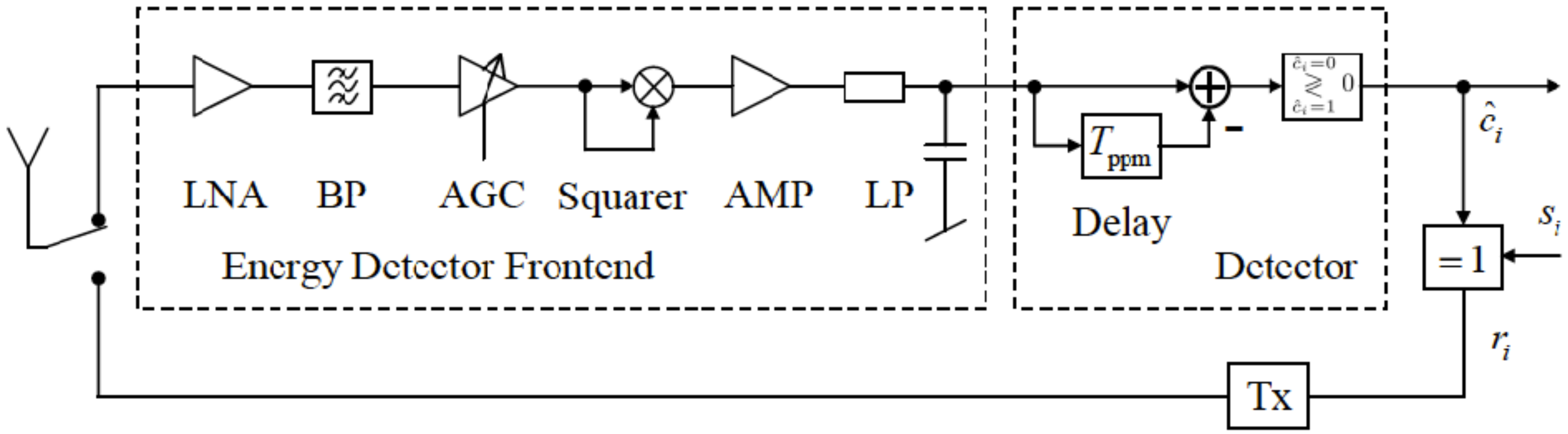
What I didn't talk about (synchronization, preambles, ...).

Ongoing implementations ...
...

Other Implementation Efforts

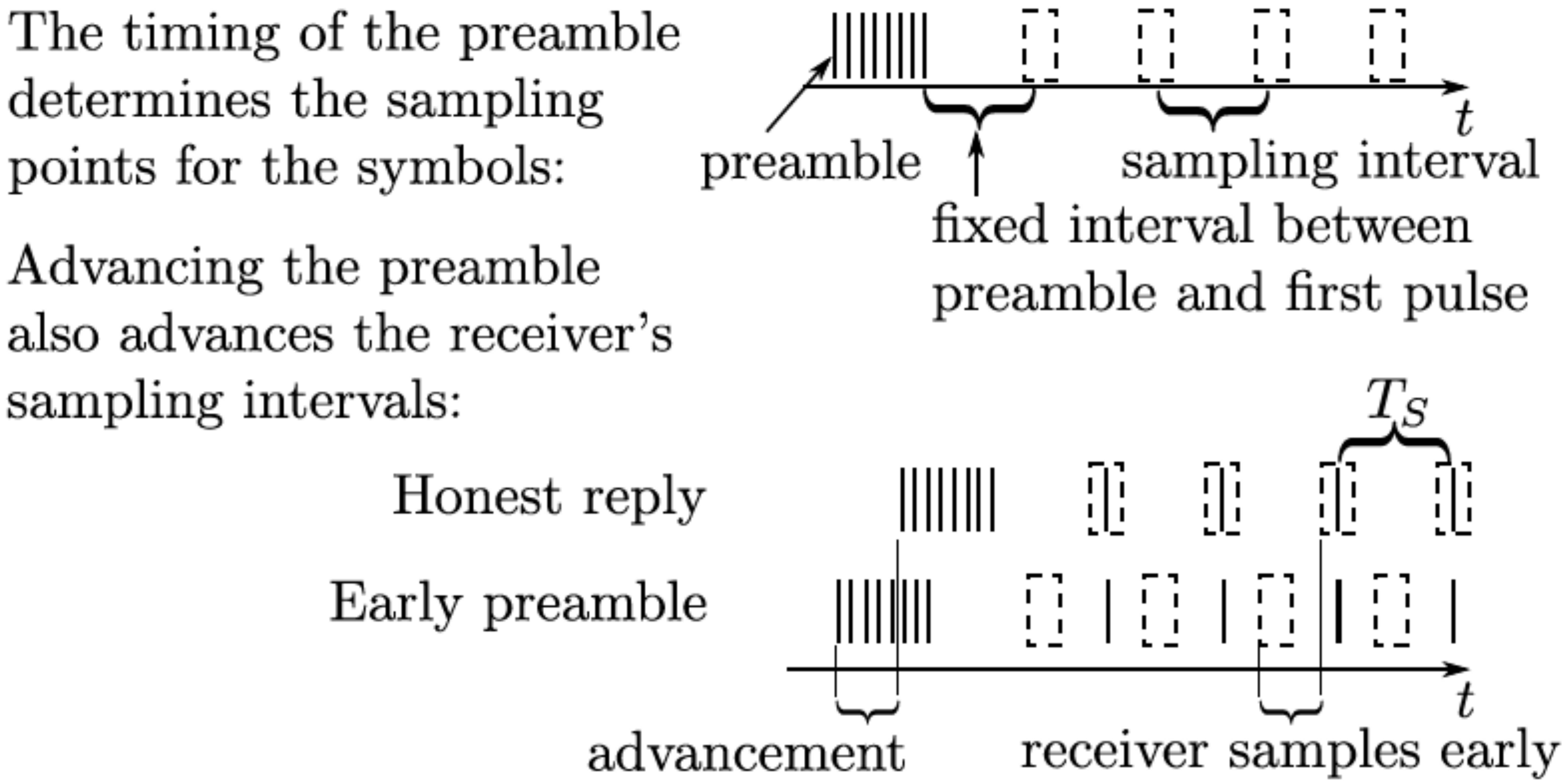
Going back to XOR.

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



[Tipp15] N. Tippenhauer, H. Luecken, M. Kuhn and S. Capkun,
UWB Rapid-Bit-Exchange System for Distance Bounding, ACM WiSec 2015

Direct Time Measurement vs “Distance Commitment”



The timing of the preamble determines the sampling points for the symbols:

Advancing the preamble also advances the receiver’s sampling intervals:

Allows for the prover to respond before it even decodes the received symbol / bit. [Tipp15, Singh17]

[Tipp15] N. Tippenhauer, H. Luecken, M. Kuhn and S. Capkun,
UWB Rapid-Bit-Exchange System for Distance Bounding, ACM WiSec 2015


RangingApplication
continous verifier
UWB CONTROLLER
distance
7.0
6.0
5.0
4.0
3.0
2.0
1.0
distance [m]
sample
distance[m] 0.14
Reconnect
update ● run ○ hold
display ● distance ○ signal
show raw value ○ off ● on
delay [ms]
0 250 500 750 1000
0
3db
distance[m] 0.14

distance[m] 0.14

update ● run ○ hold

display ● distance ○ signal

show raw value ○ off ● on

delay [ms] 0

distance[m] 0.14

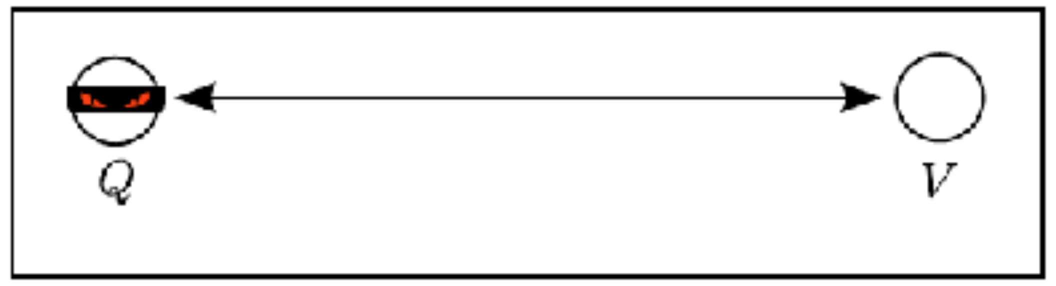
Protocol Analysis

Two main protocol constructs:

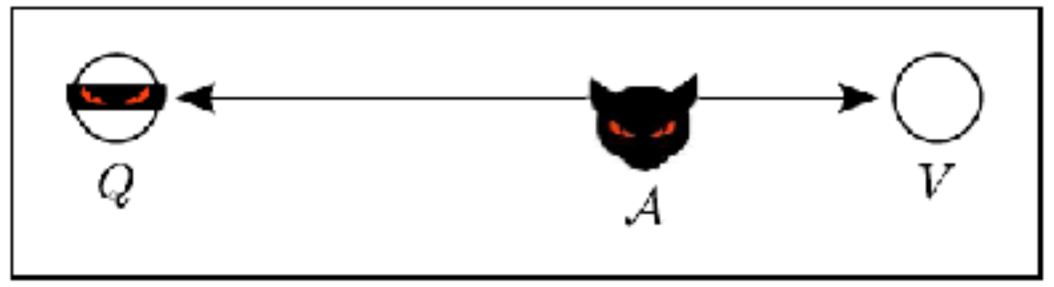
- Hancke-Kuhn
- Brands-Chaum

Three main attacks considered:

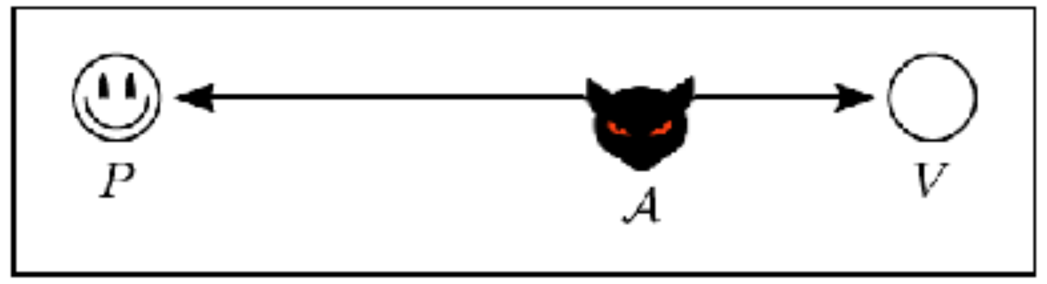
Distance Fraud



Terrorist Fraud



Mafia Fraud



Protocol Analysis

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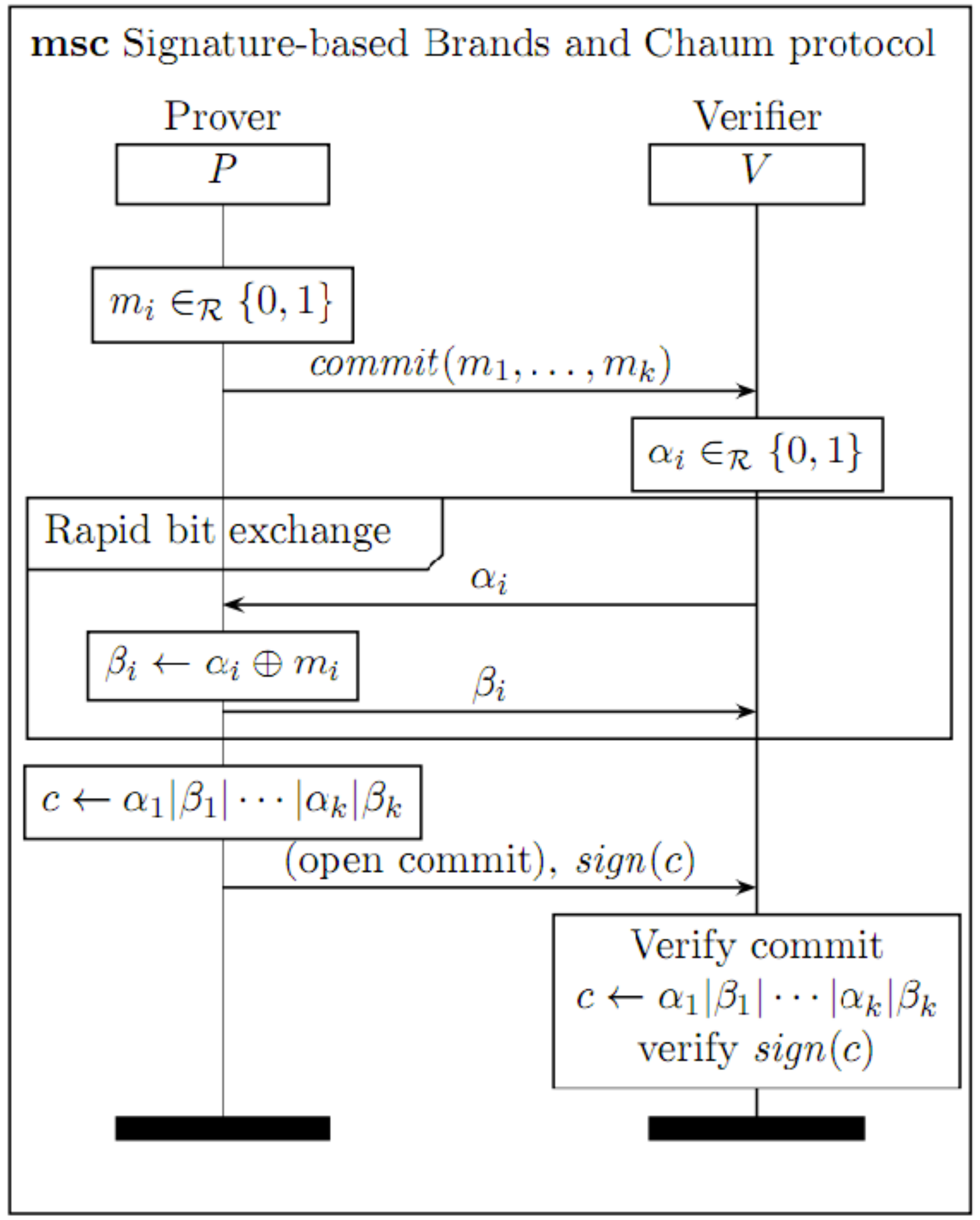
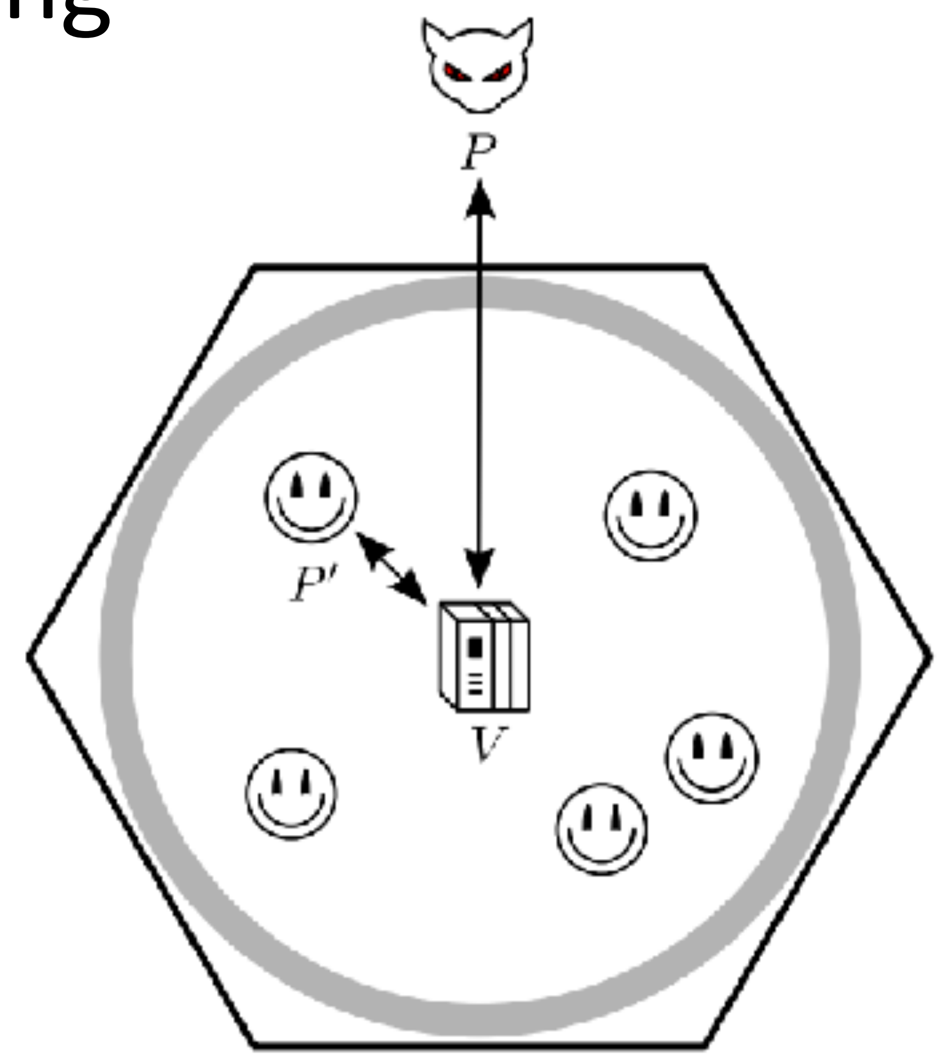
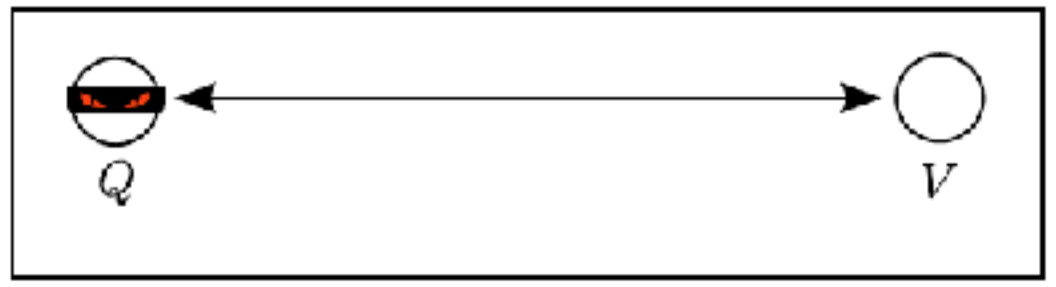


Protocol Analysis

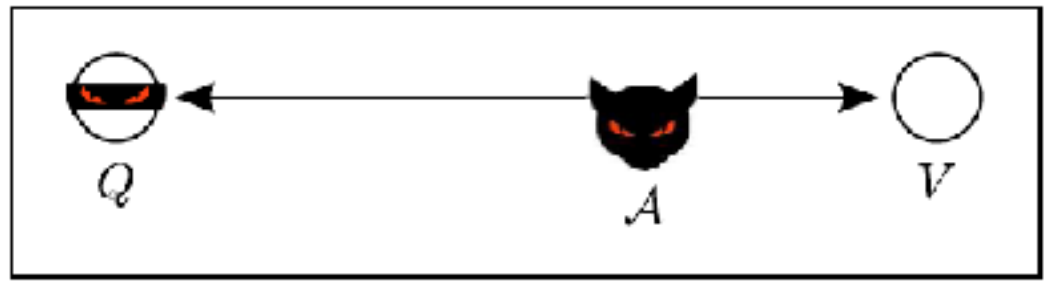
Novel attack: Distance Hijacking



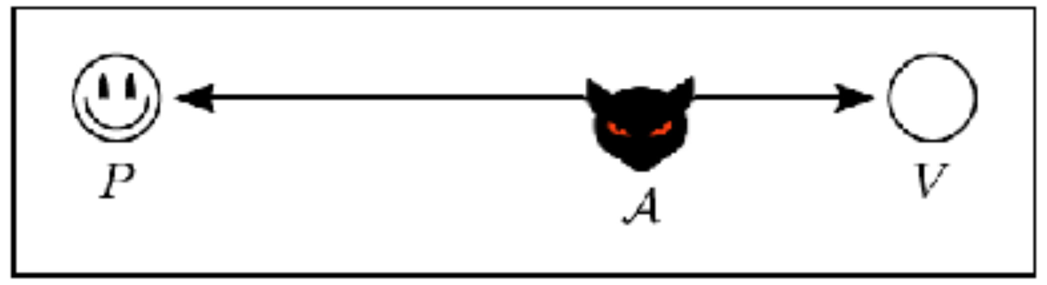
Distance Fraud



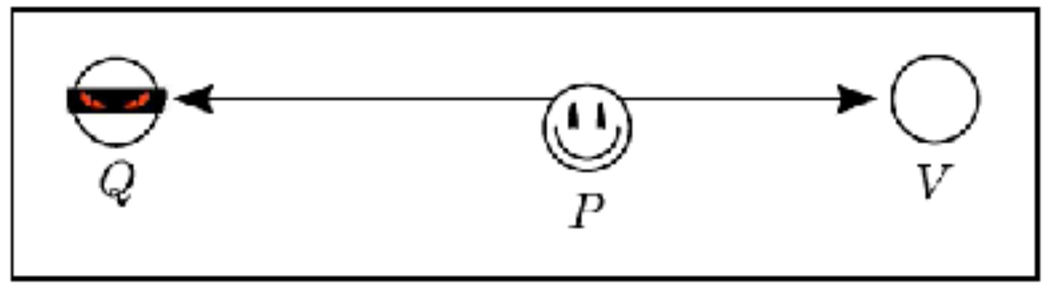
Terrorist Fraud



Mafia Fraud

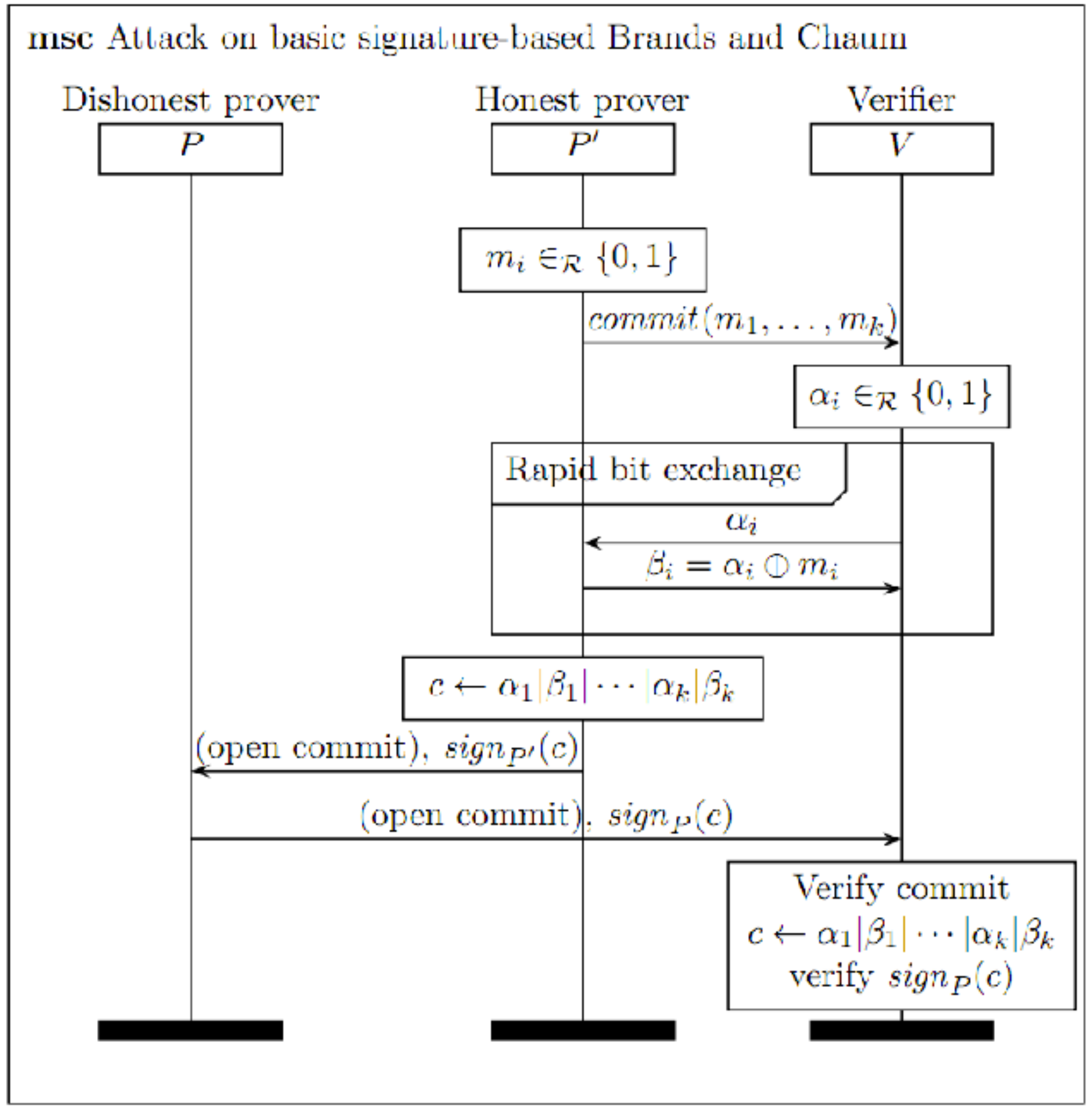


Distance Hijacking



Protocol Analysis

Distance Hijacking on Brands and Chaum



Protocol Analysis

More Distance Hijacking

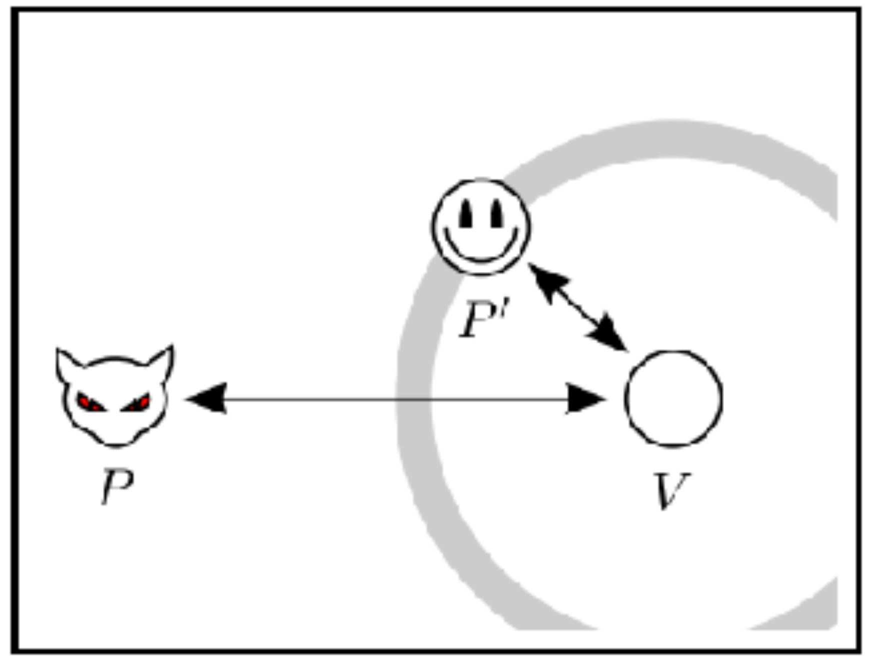


Figure 7: Scenario in which V accepts protocol sessions from multiple provers, here P and P', where Distance Hijacking may be a threat.

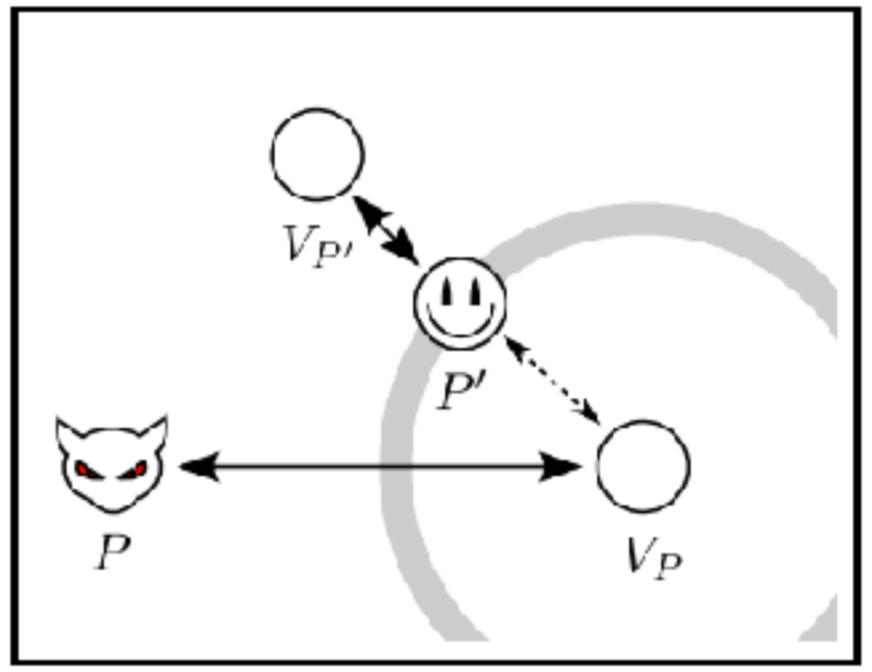


Figure 8: Scenario with multiple prover/verifier pairs, where V_x only accepts sessions from x. Even in this case, Distance Hijacking may be possible.

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)

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

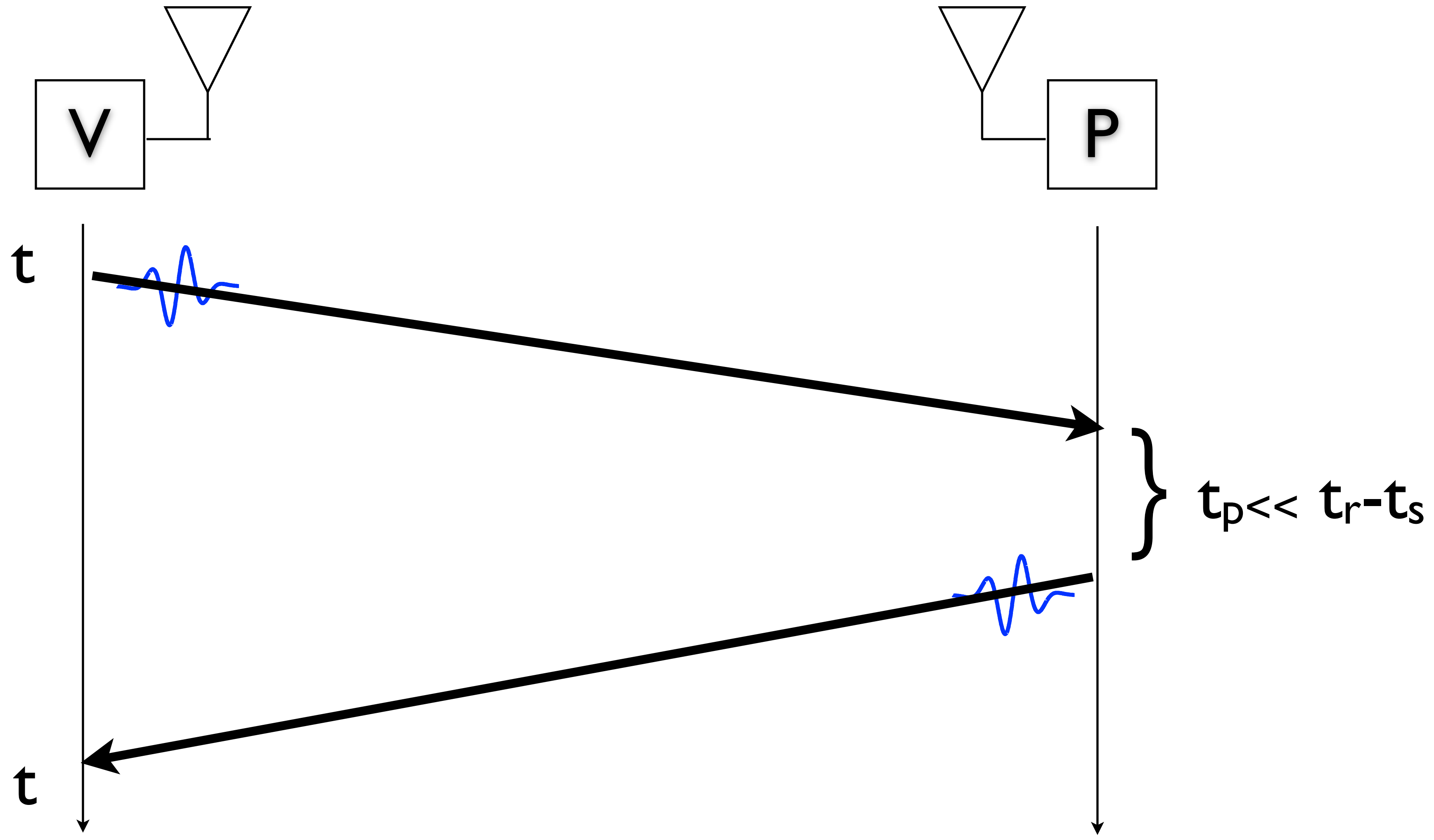
- Compute a 'correct' location of a (trusted) device in the presence of an attacker. *(Secure Localization)*
- Verify the correctness of a location of an untrusted device. (that e.g., claims a certain location) *(Location Verification)*

Distance Bounding

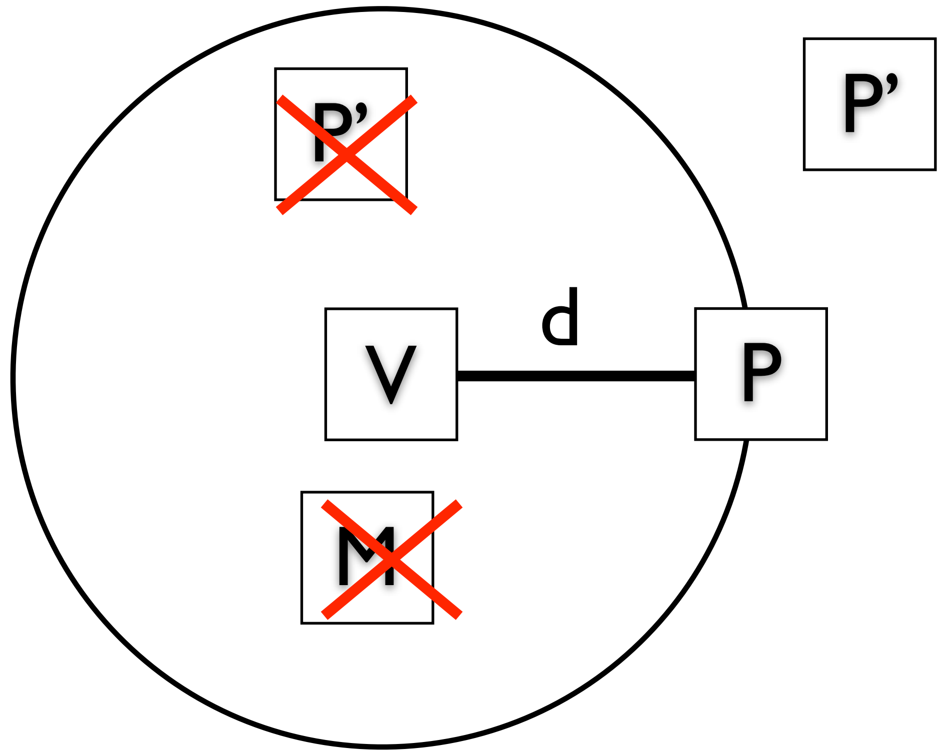
- P can always pretend to be further from V
- M can always convince P and V that they are further away

*=> 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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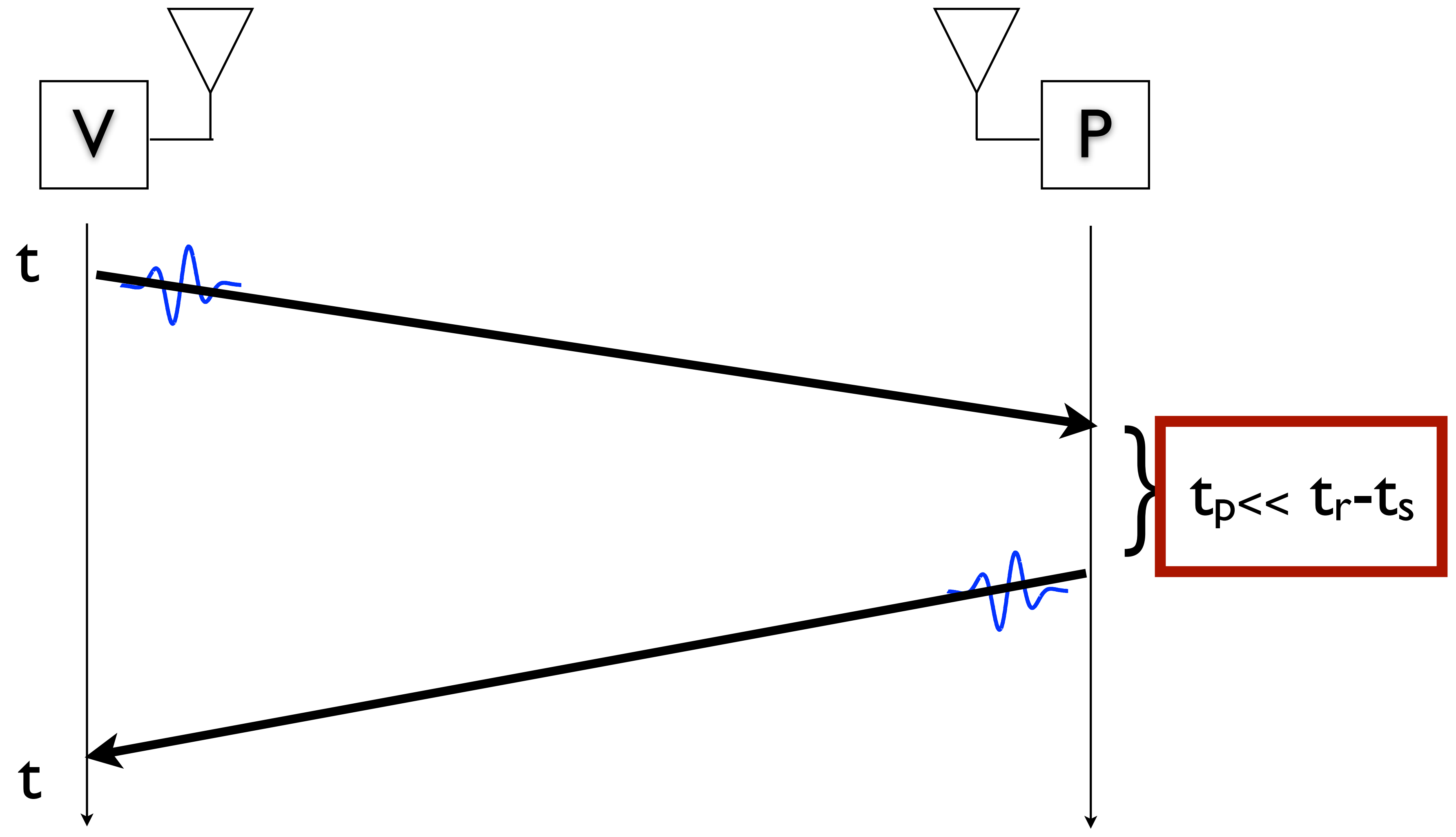
Ranging



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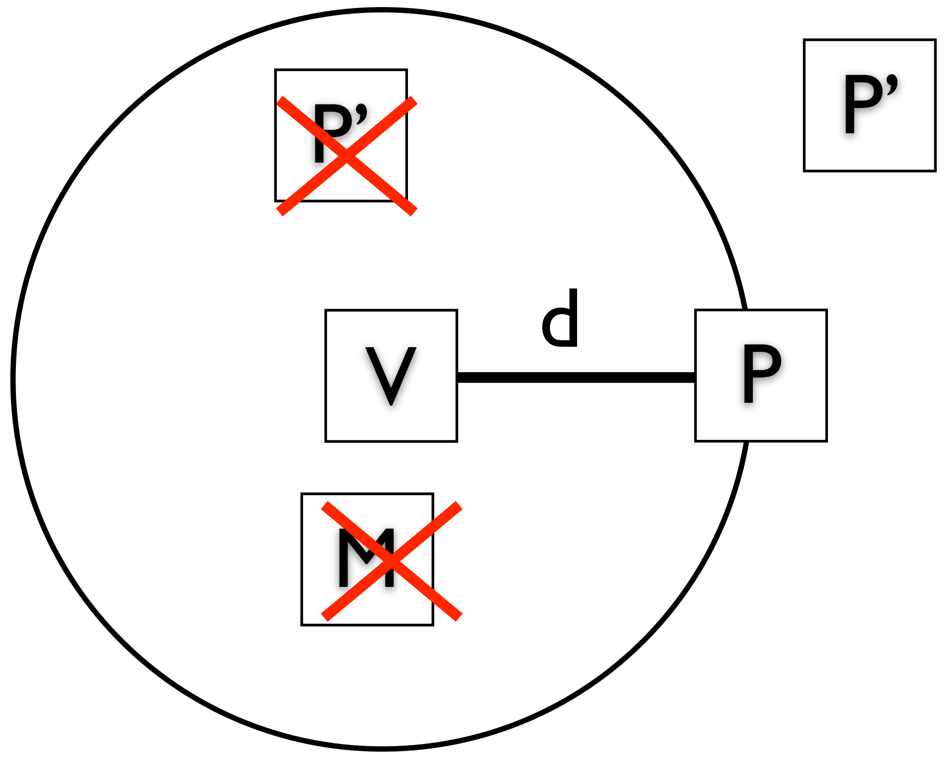

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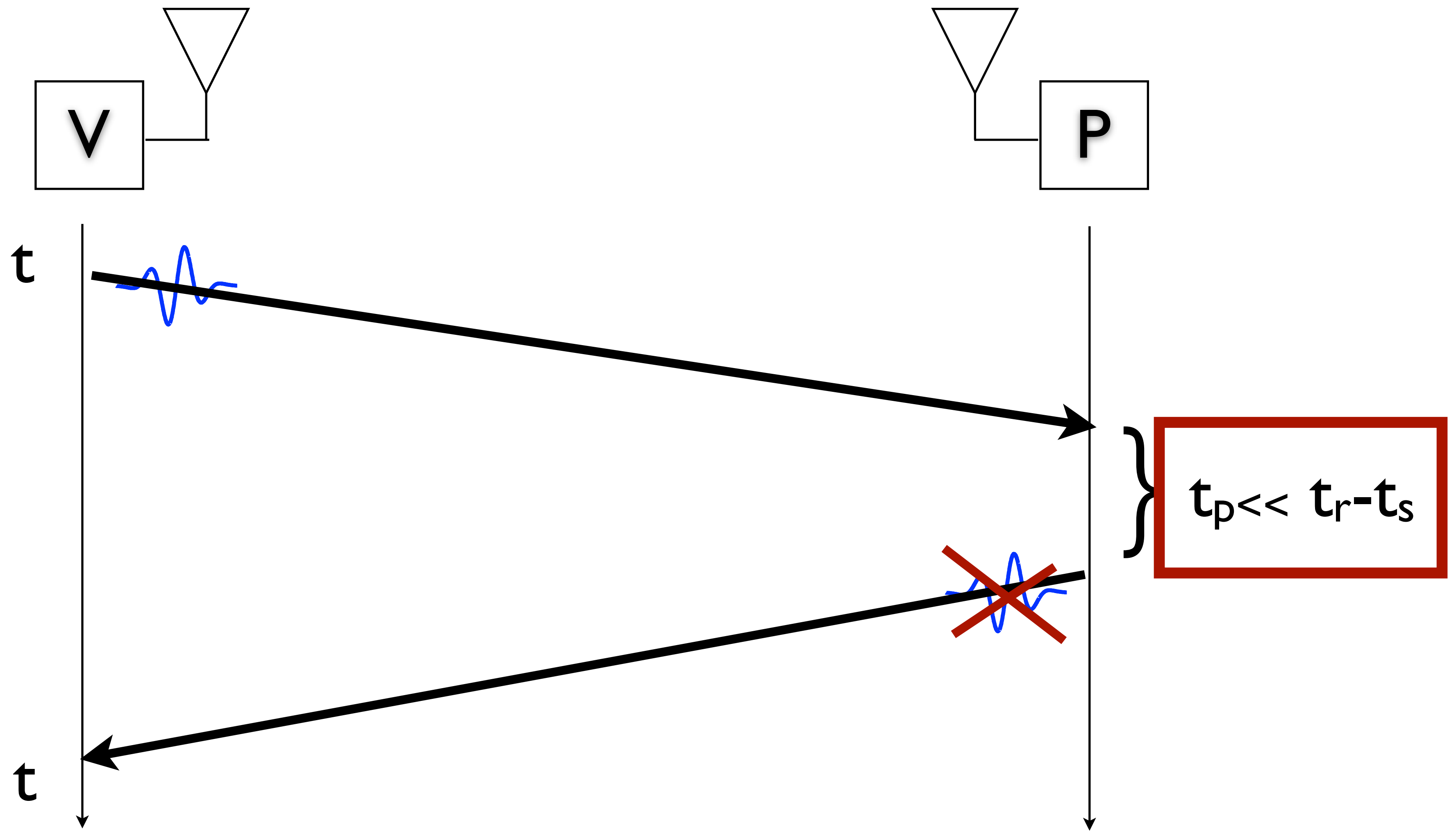
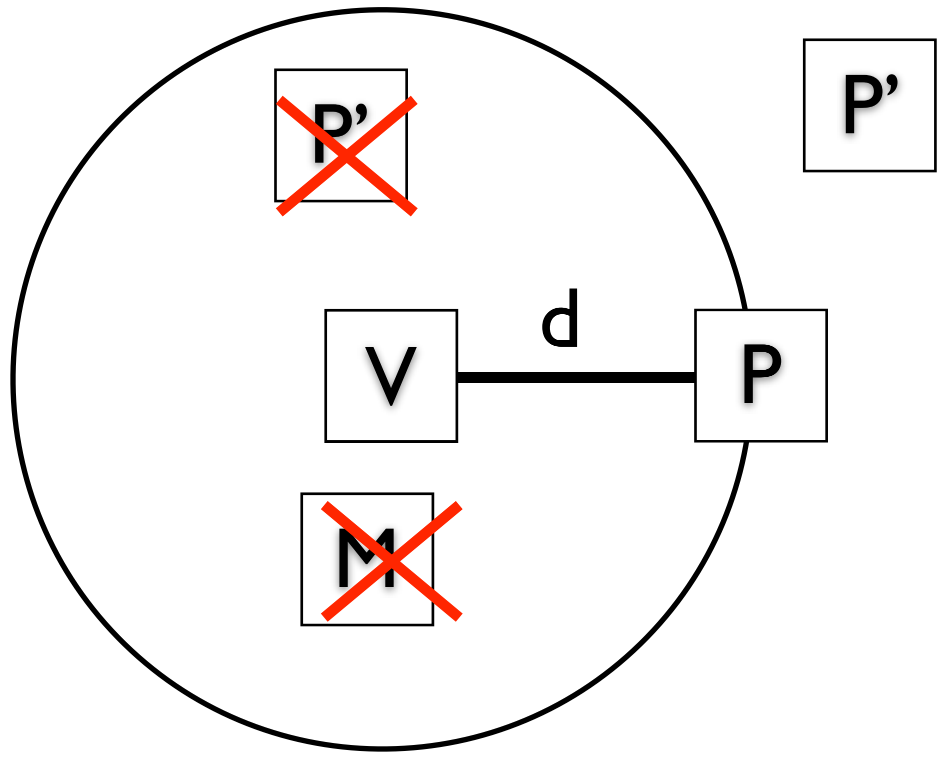
Ranging



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



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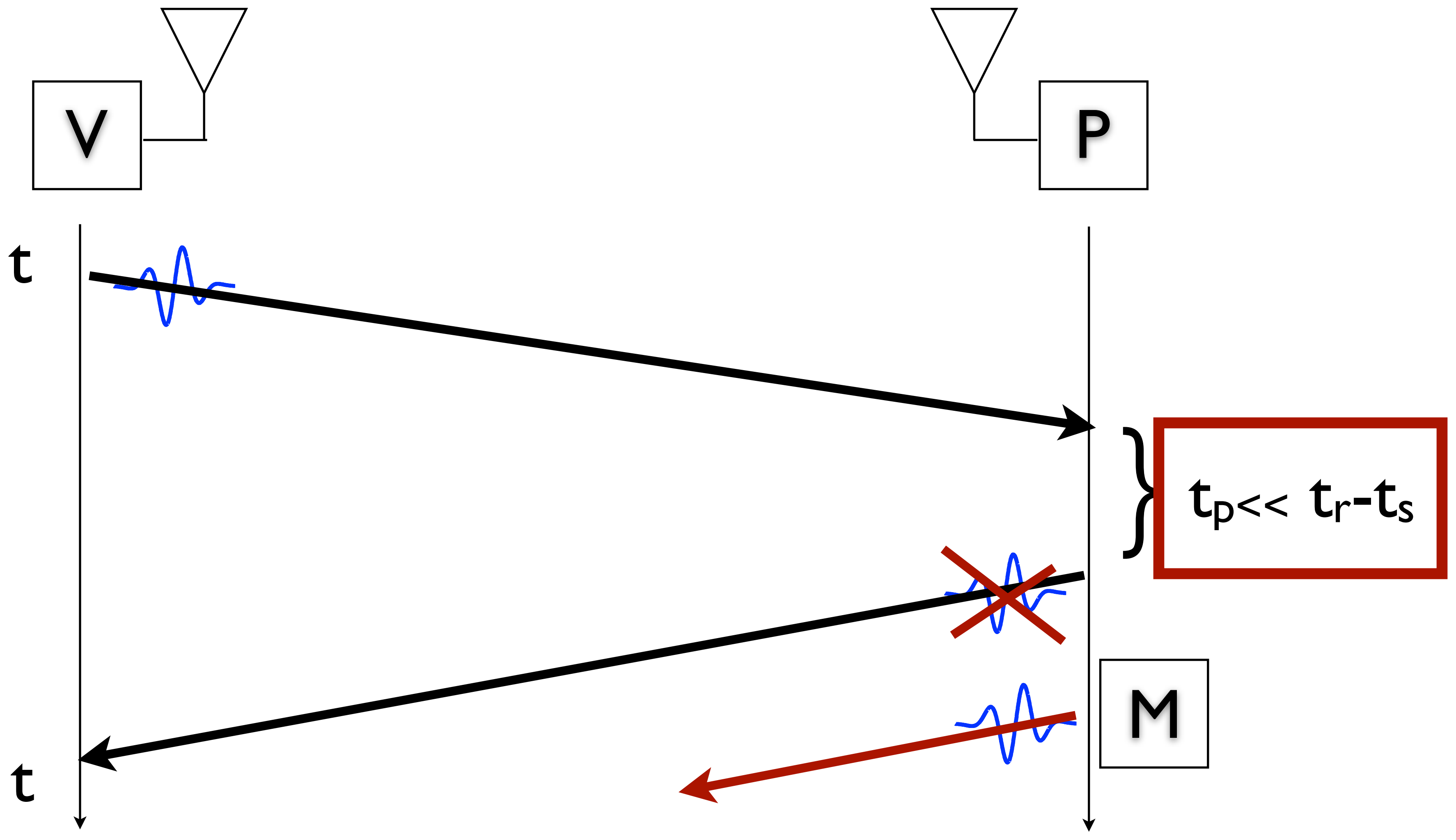
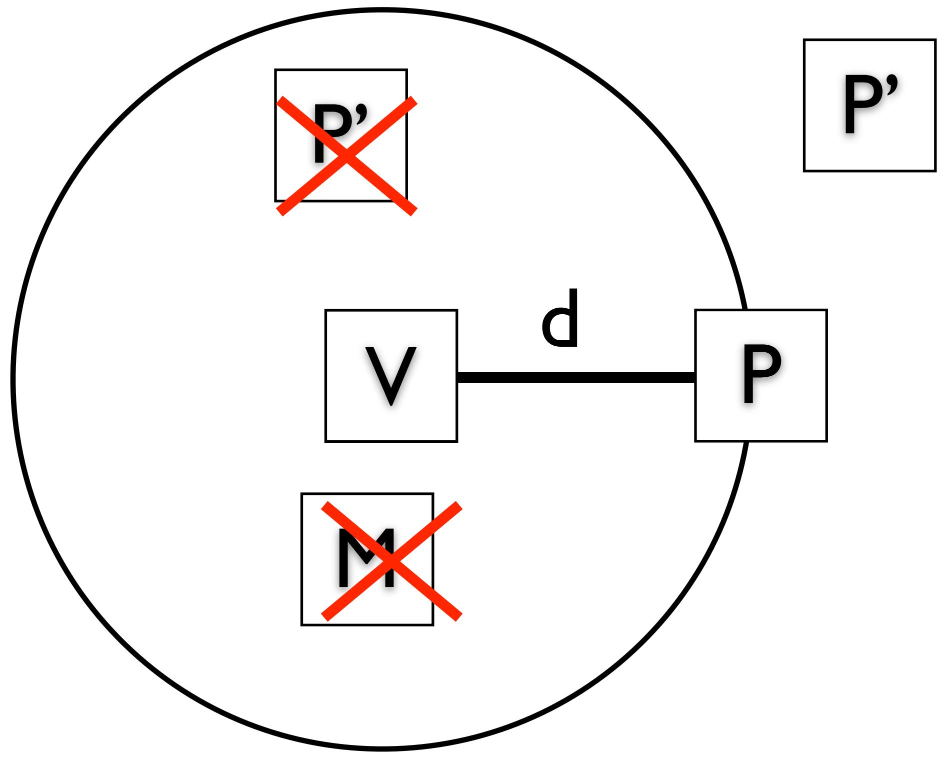


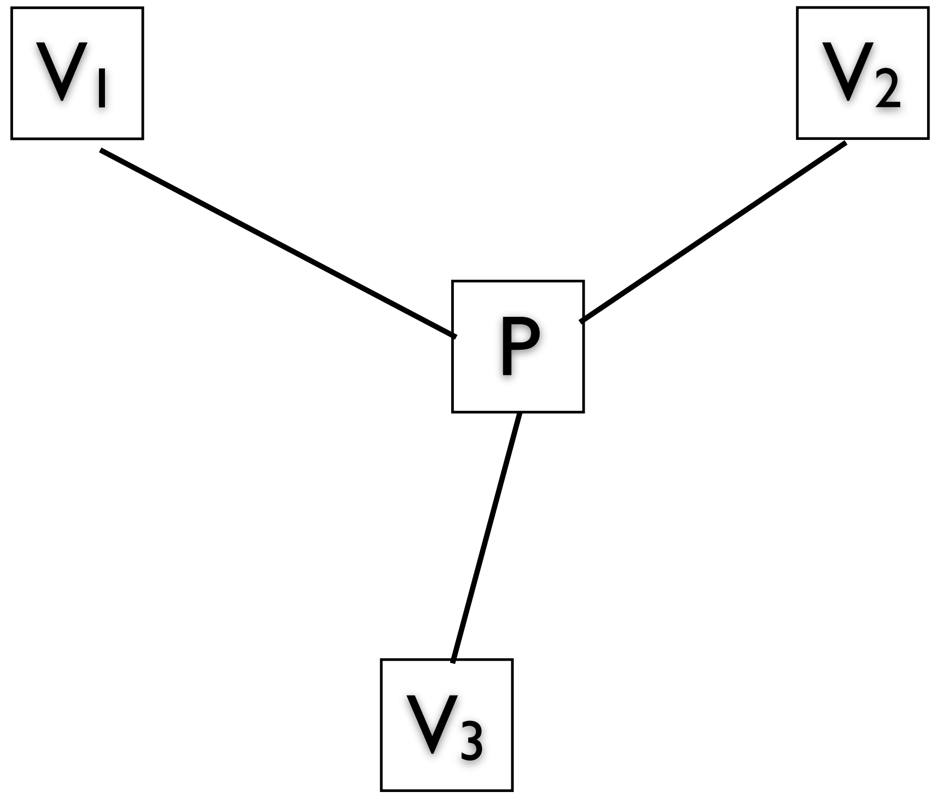
$d = (t_r - t_s - t_p)c/2$



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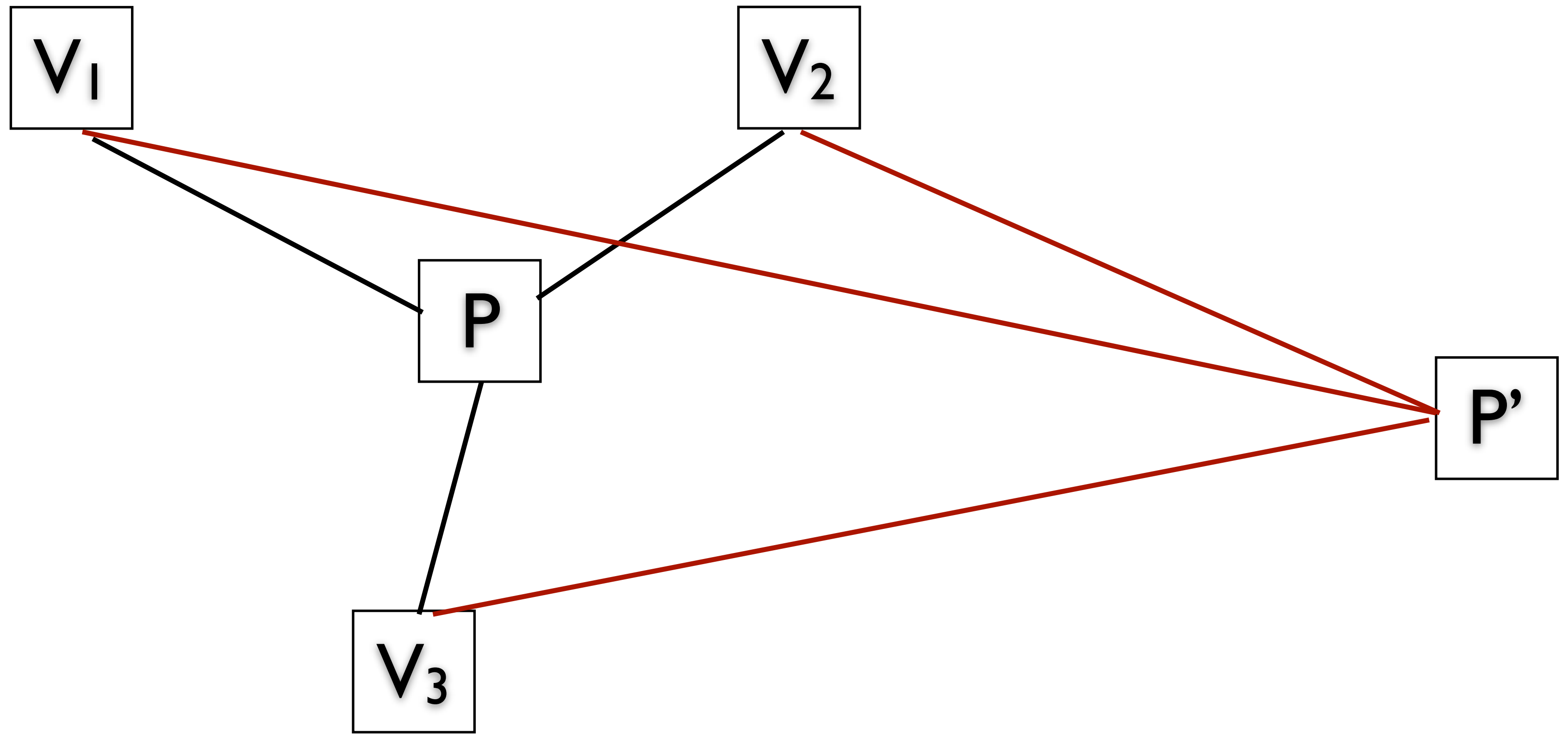
Distance enlargement is easy, distance reduction is prevented using distance bounding protocols

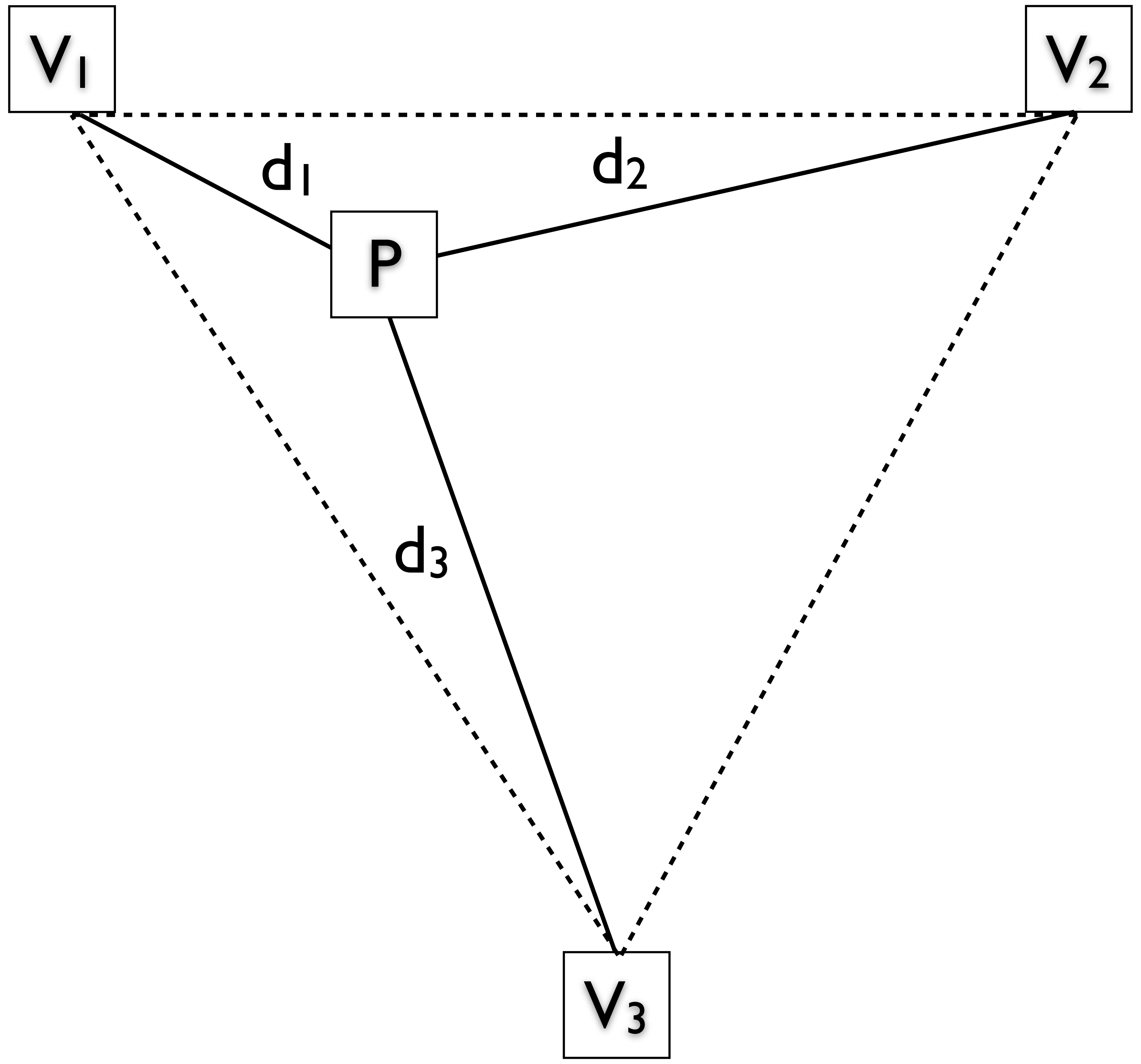
- *So can we realize Location Verification or Secure Localization using Distance Bounding protocols?*



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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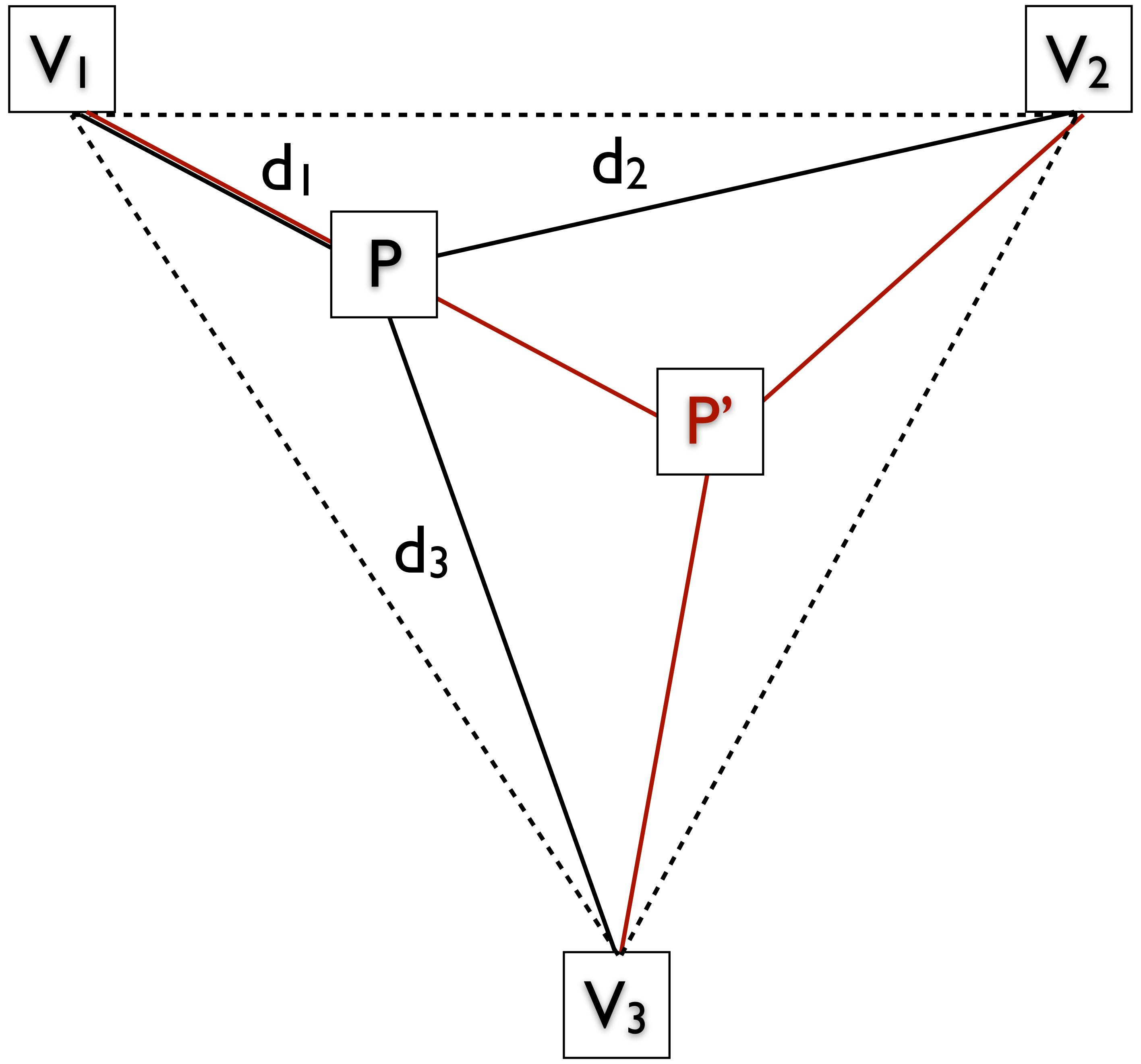

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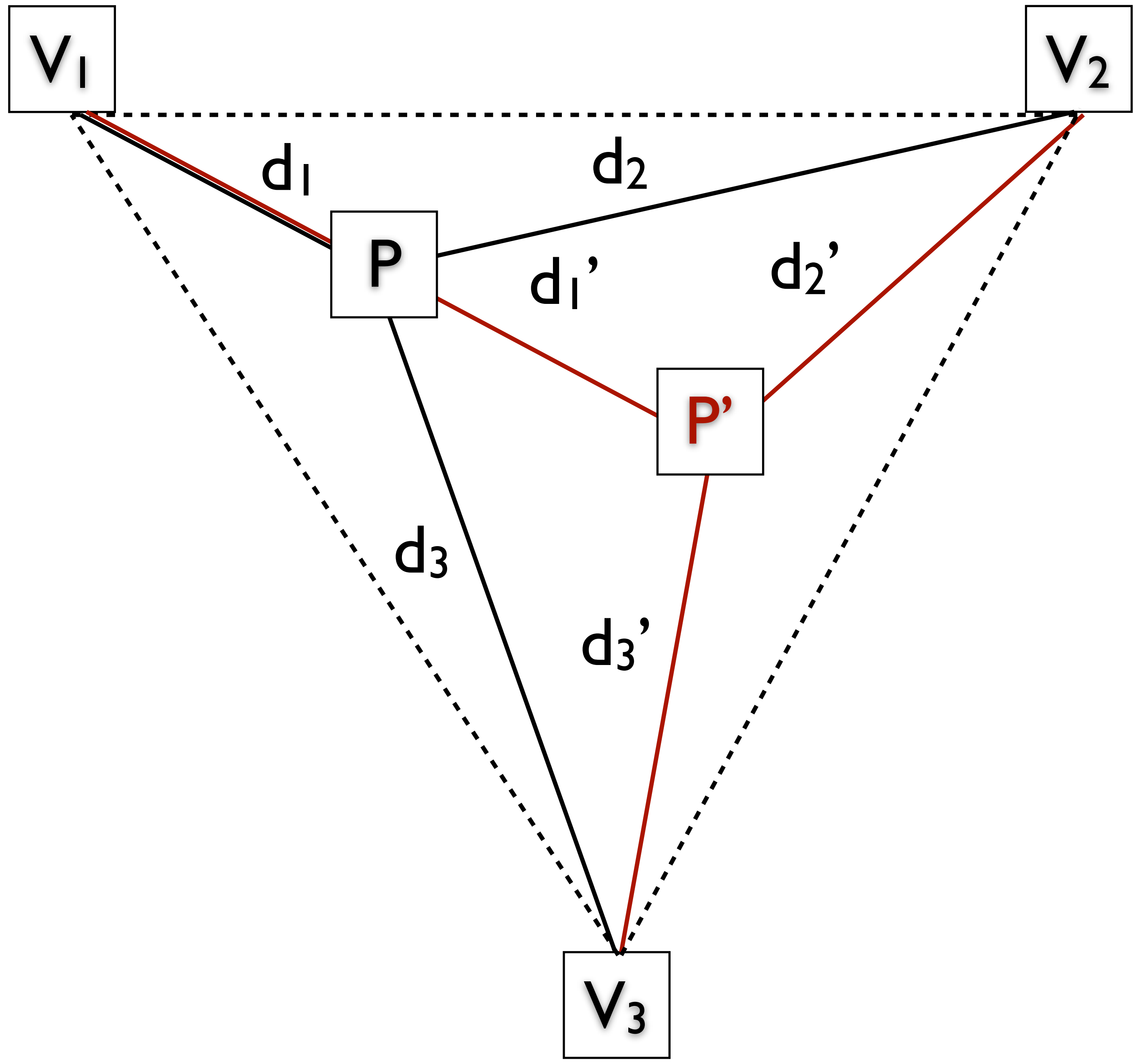
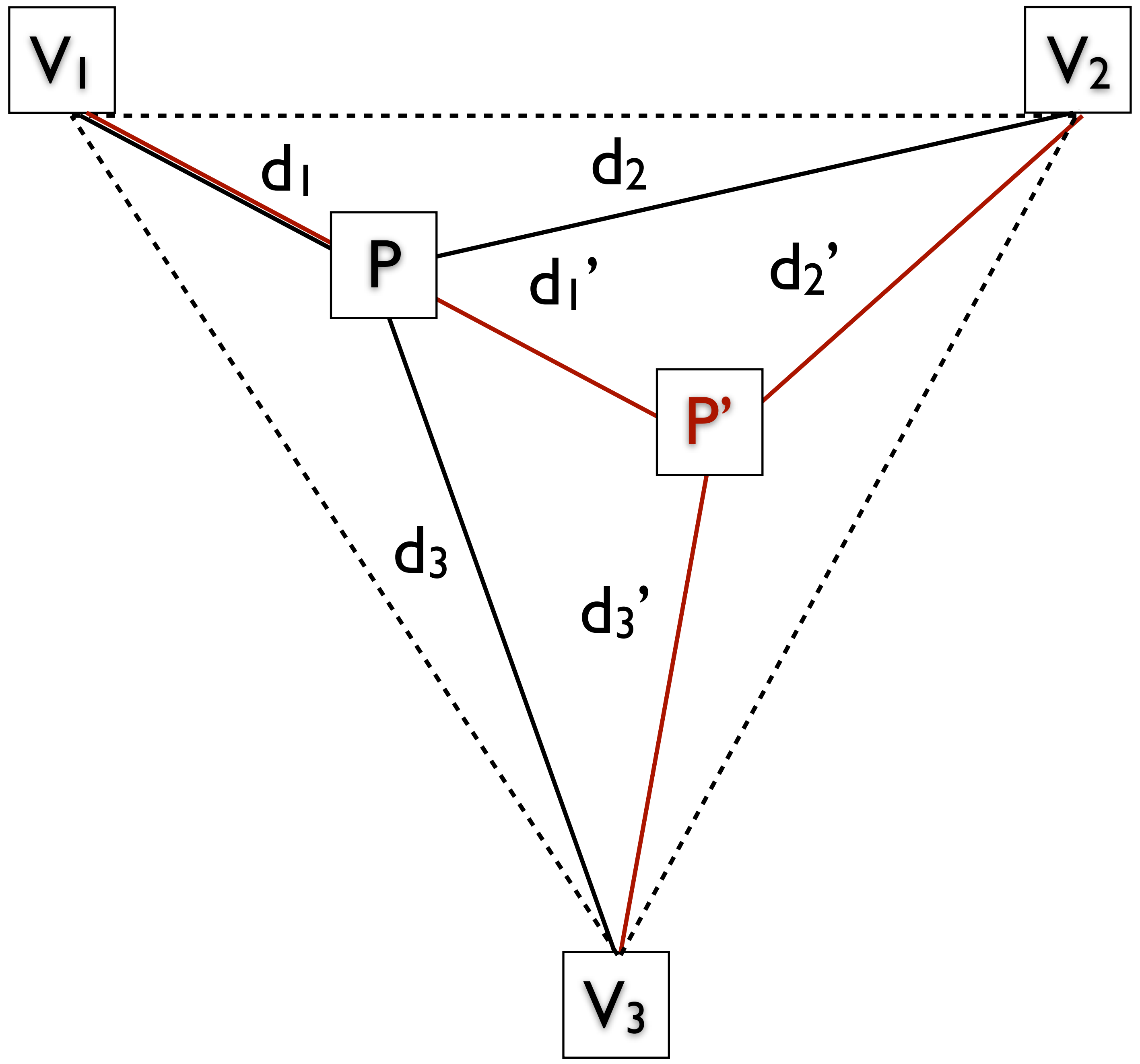


P→P' => d2'<d2

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***



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Verifiable Multilateration

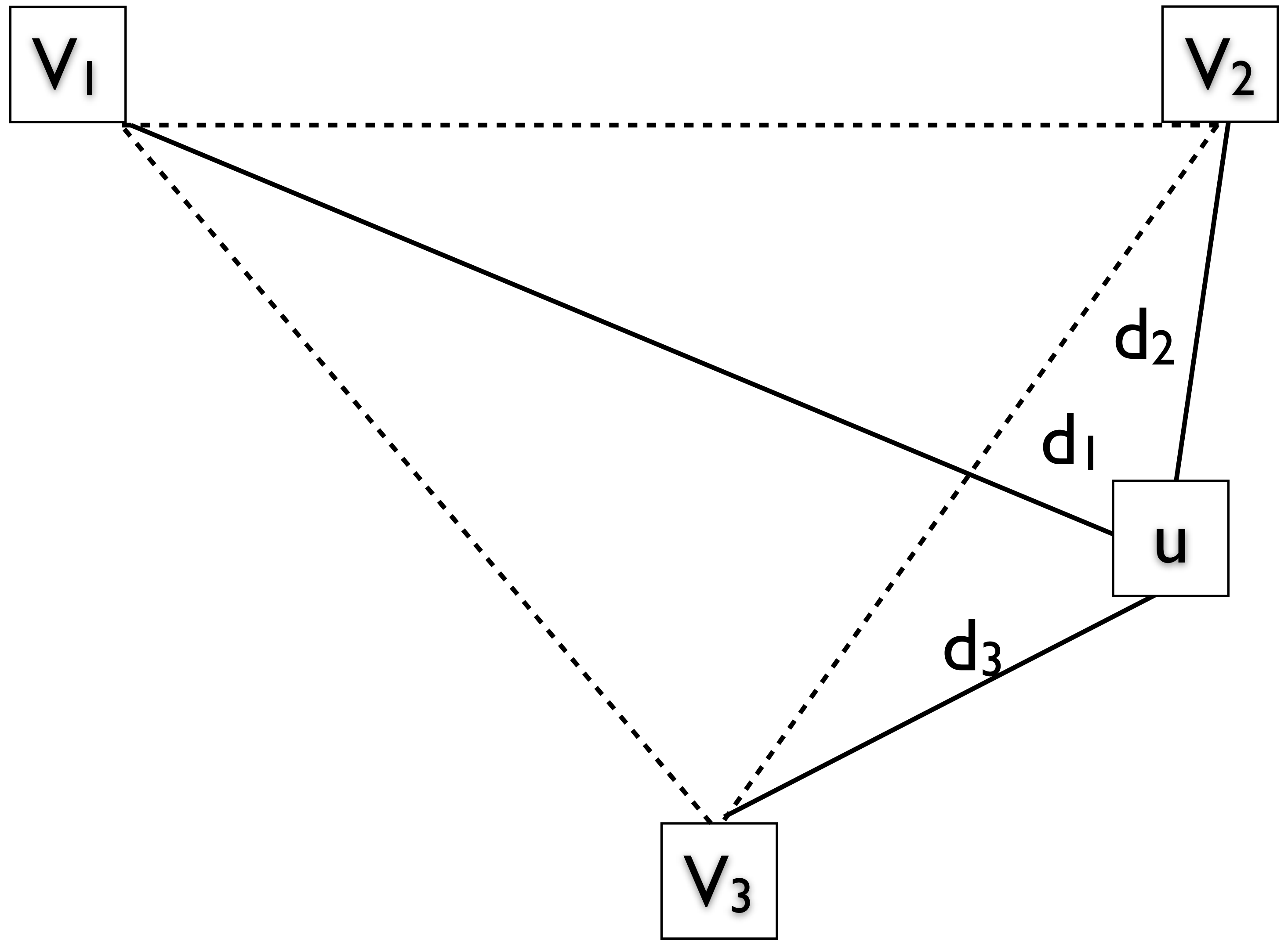
The algorithm and the errors:

- 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
> $F(x'_u, y'_u) = \sum_{v_i \in \mathcal{T}} f_i^2(x'_u, y'_u)$
> over all estimates of u

- *Attack:*



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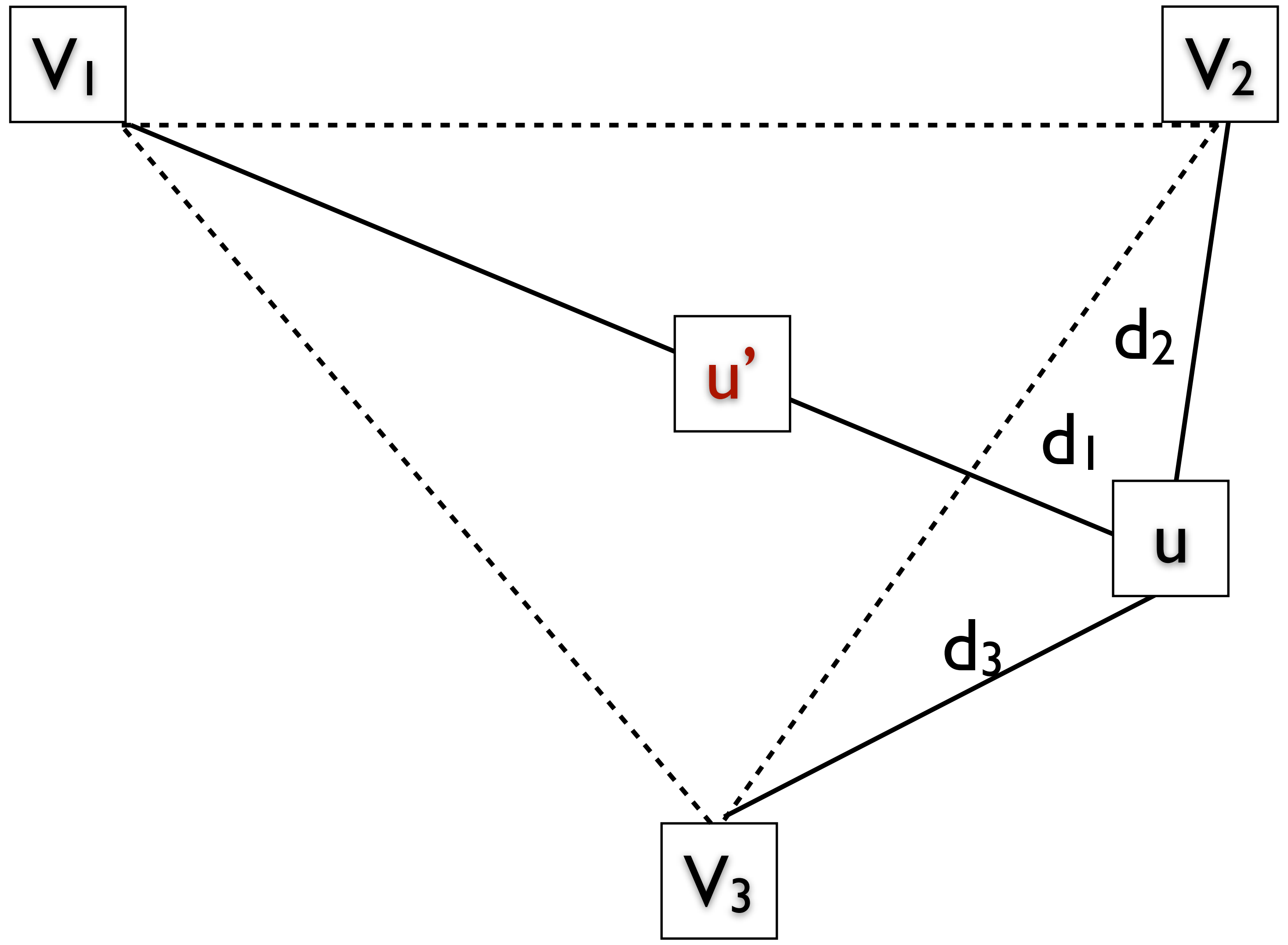

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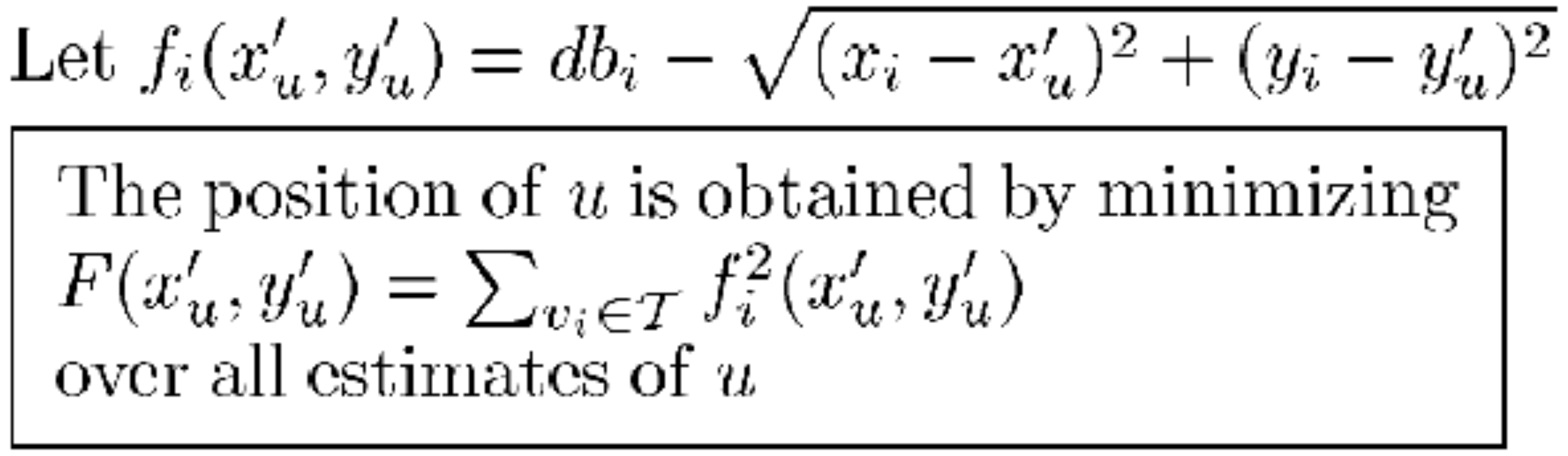

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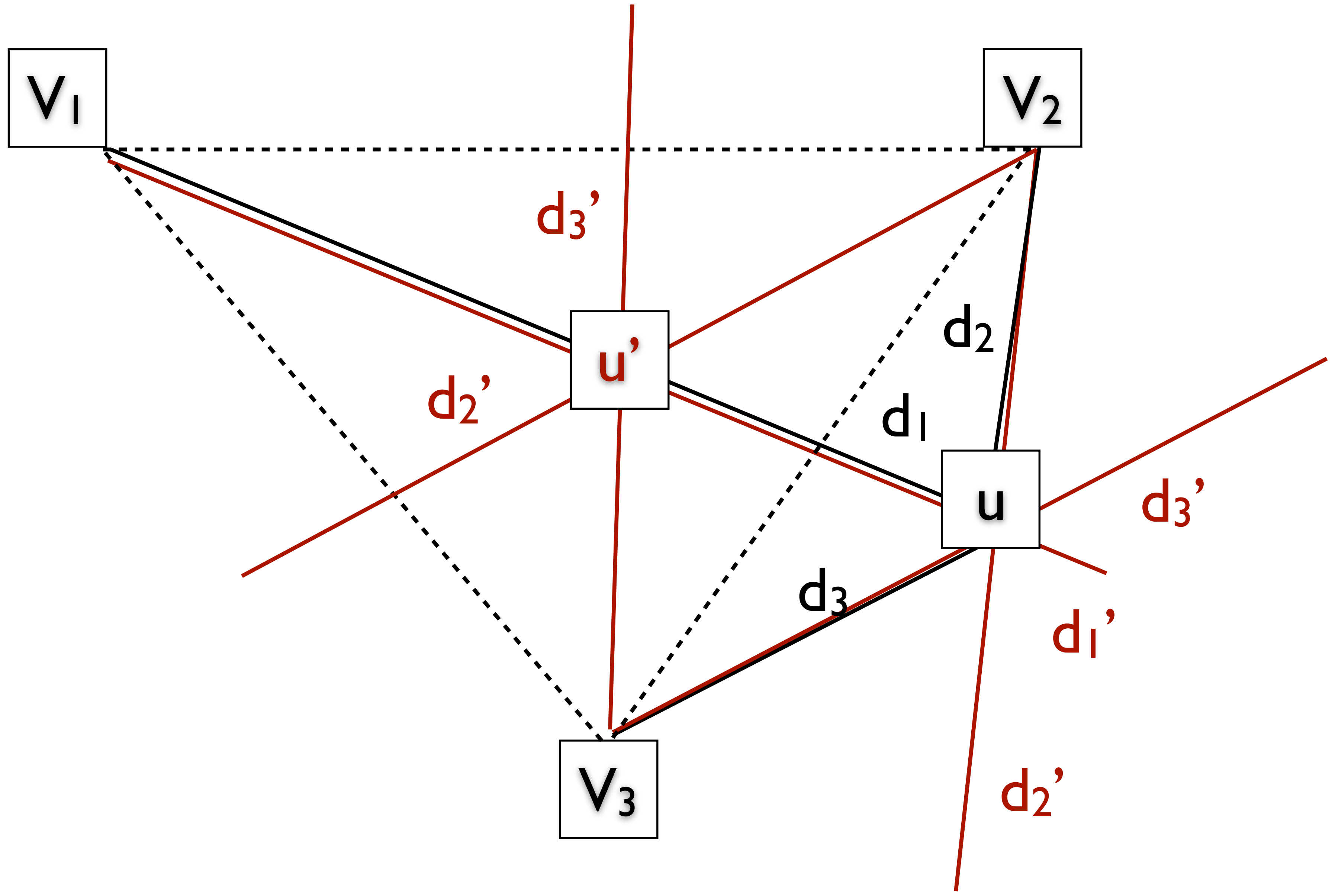
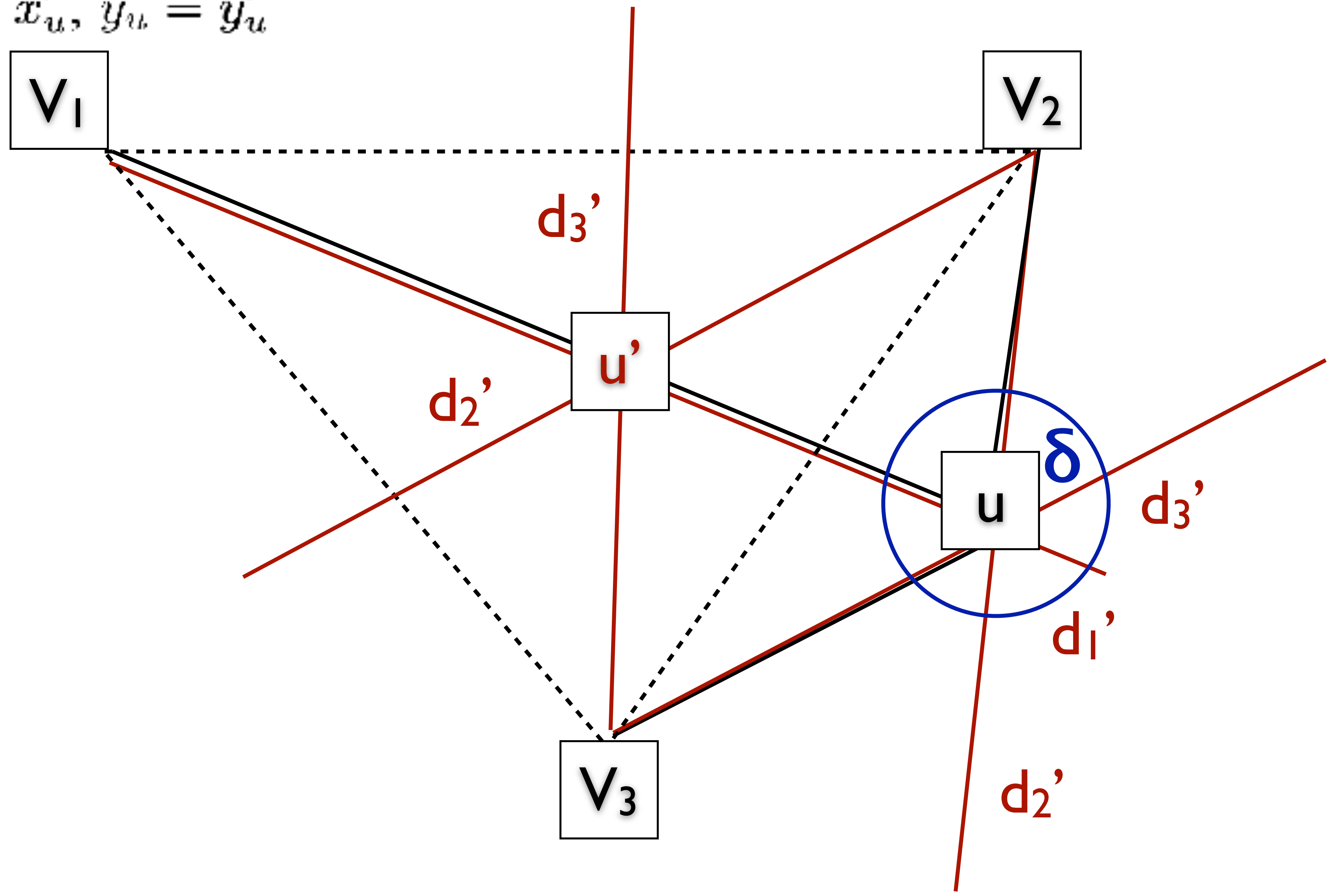


Verifiable Multilateration

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 $v_i \in \mathcal{V}$, $\boxed{|db_i - \sqrt{(x_i - x'_u)^2 + (y_i - y'_u)^2}| \le \delta}$ then
      for all $(v_i, v_j, v_k) \in \mathcal{V}^3$, if $(x'_u, y'_u) \in \triangle(v_i, v_j, v_k)$
      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
  else the position is rejected
```



Verifiable Multilateration

Collusion attacks (only with untrusted prover under location verification)

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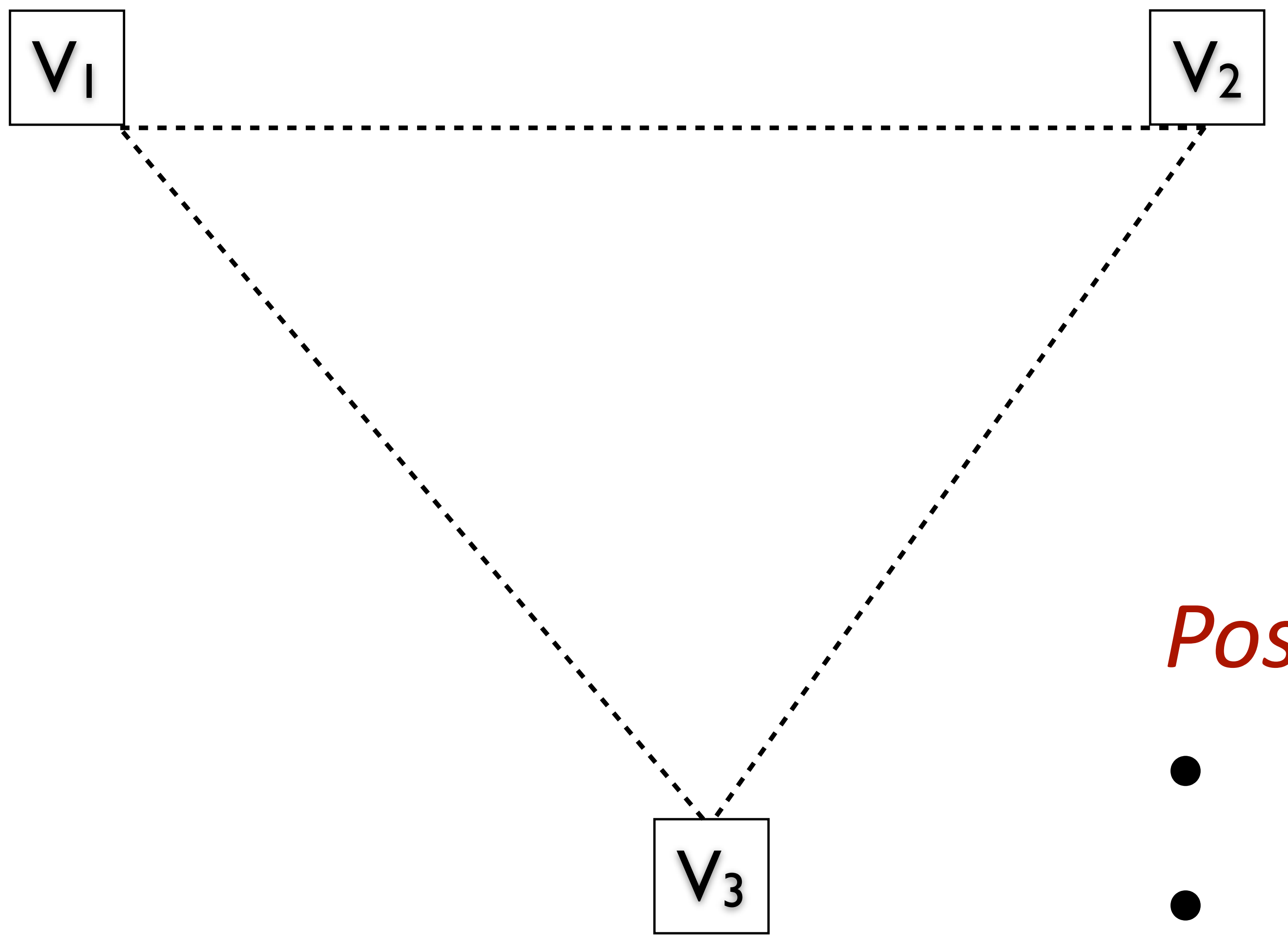

Possible protections:

- Tamper Resistance
- Device Identification

Verifiable Multilateration

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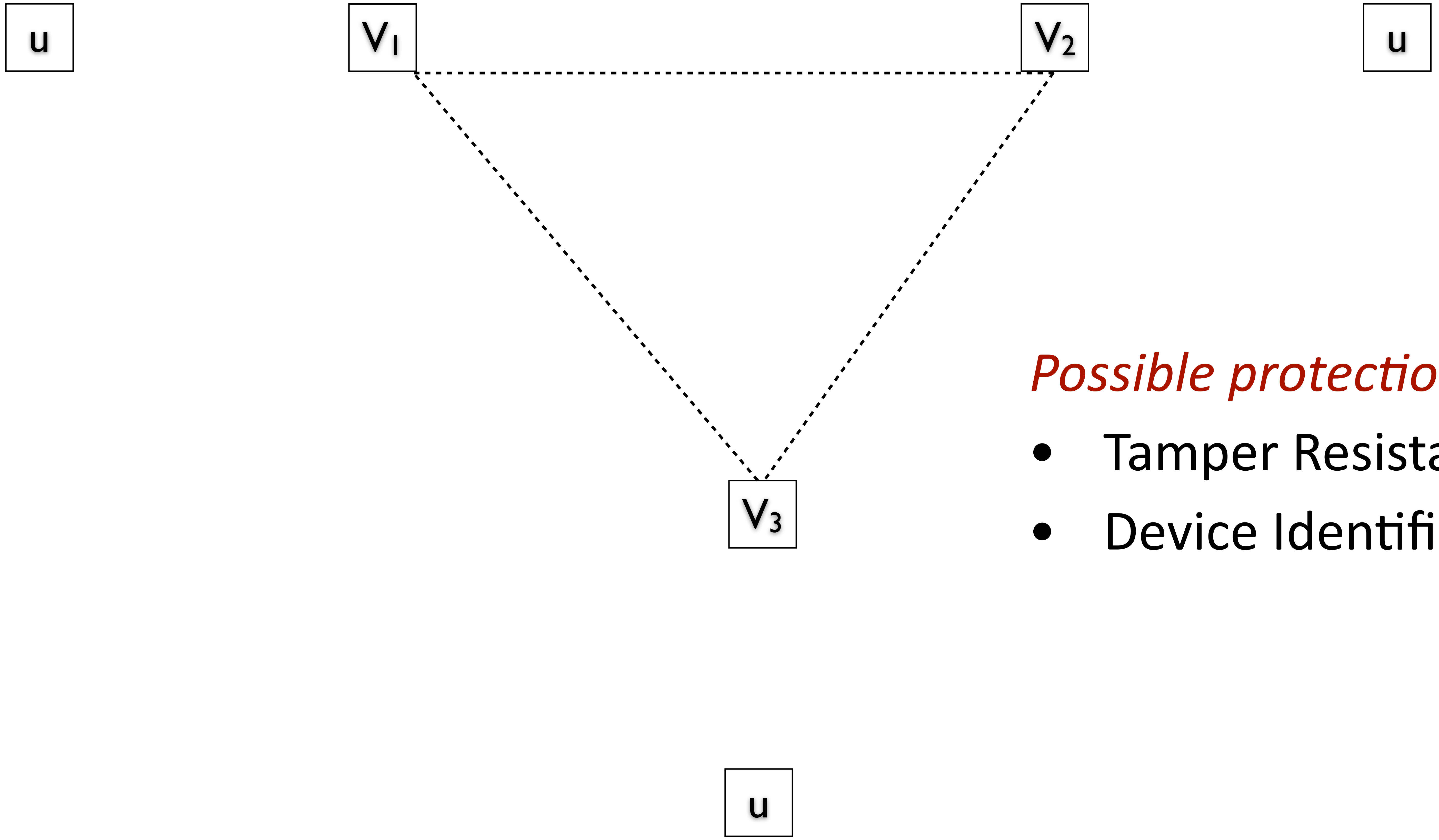

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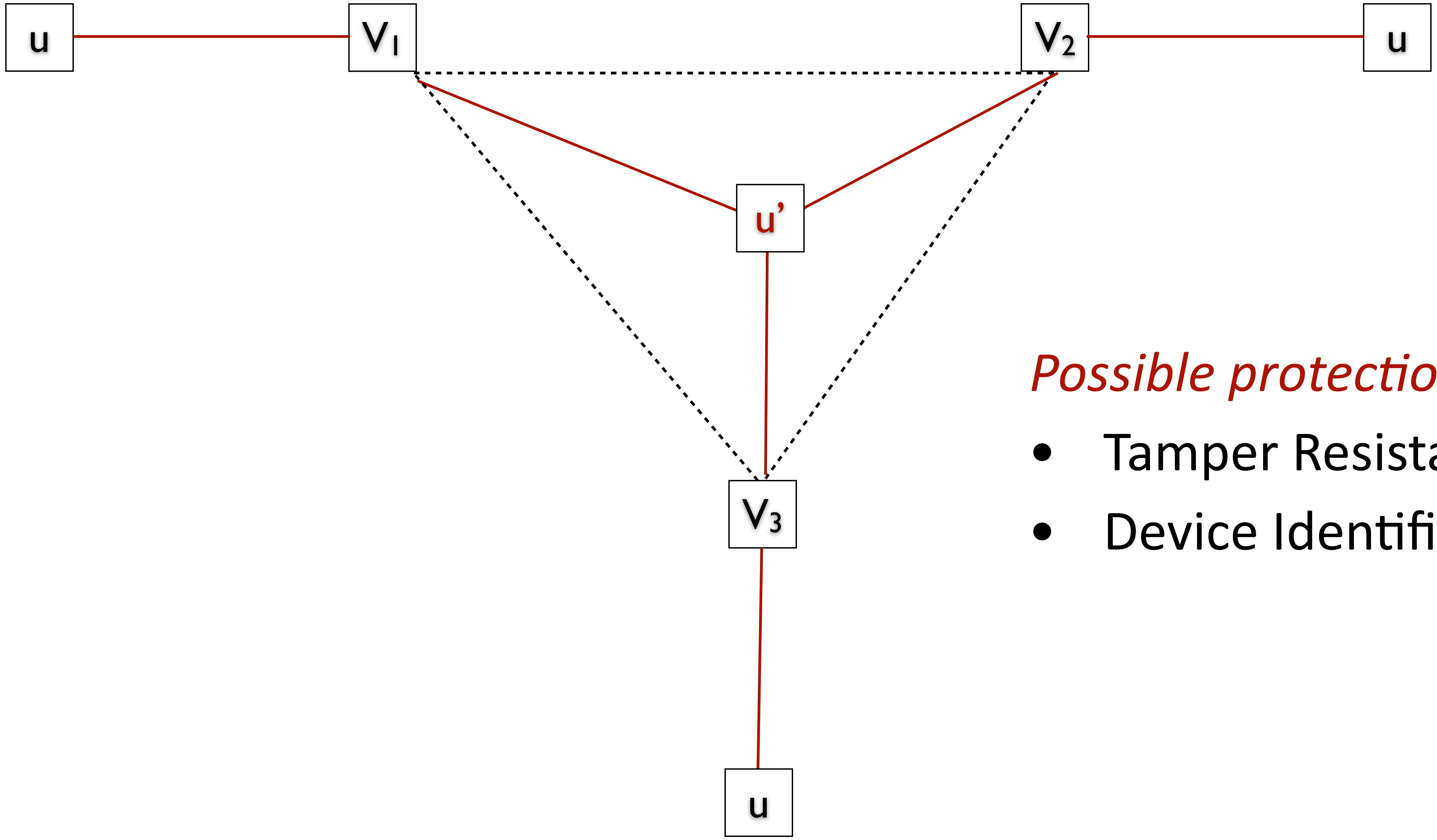

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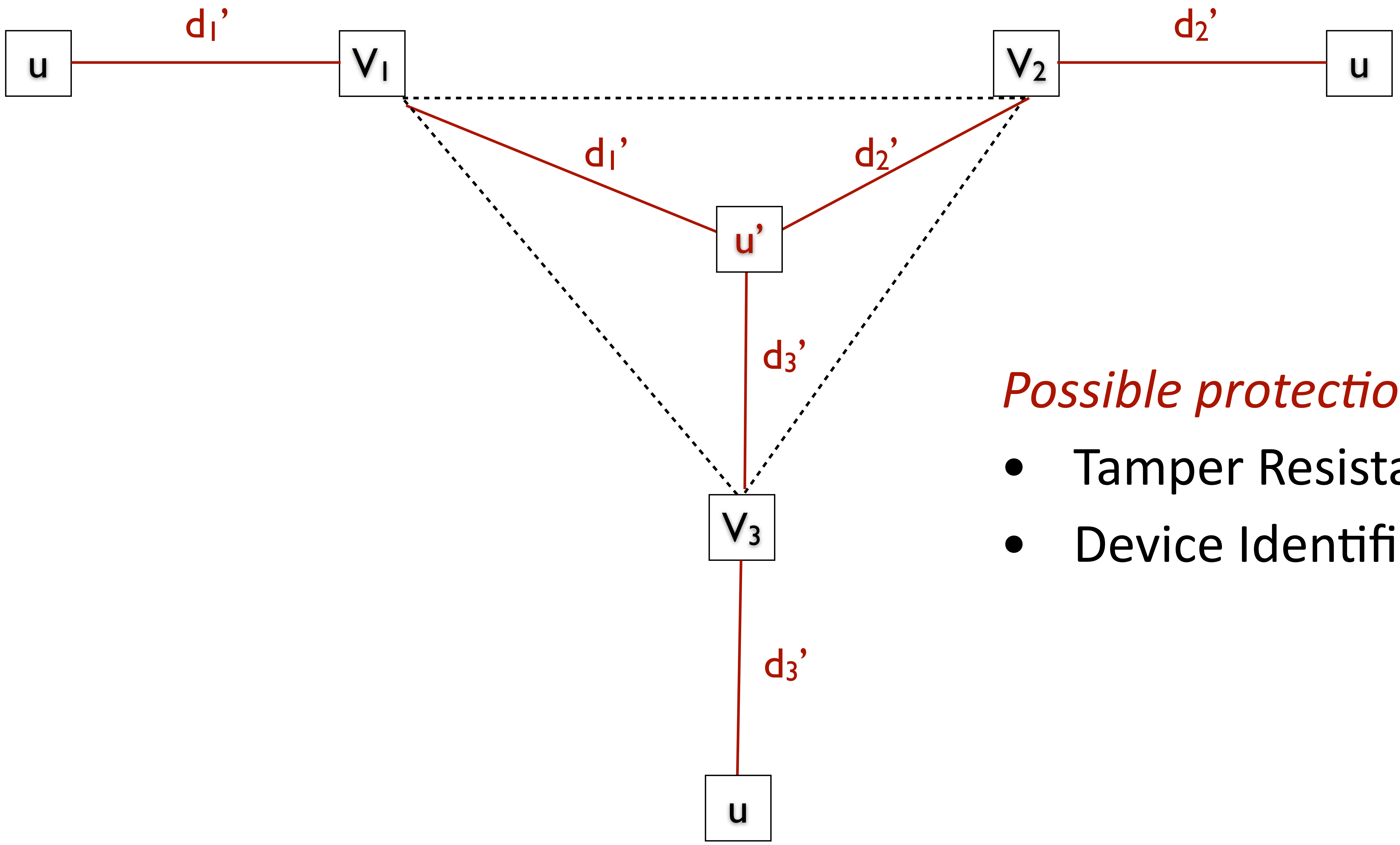

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Location Verification using Hidden and Mobile Stations *(Verifiers)*

The basic idea:

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

RF and US ranging

V

P

actual location

d

d'

claimed location

$$p(\text{successful cheating}) = p(d\text{-}d' \leq \Delta)$$

where Δ is the ranging/localization accuracy

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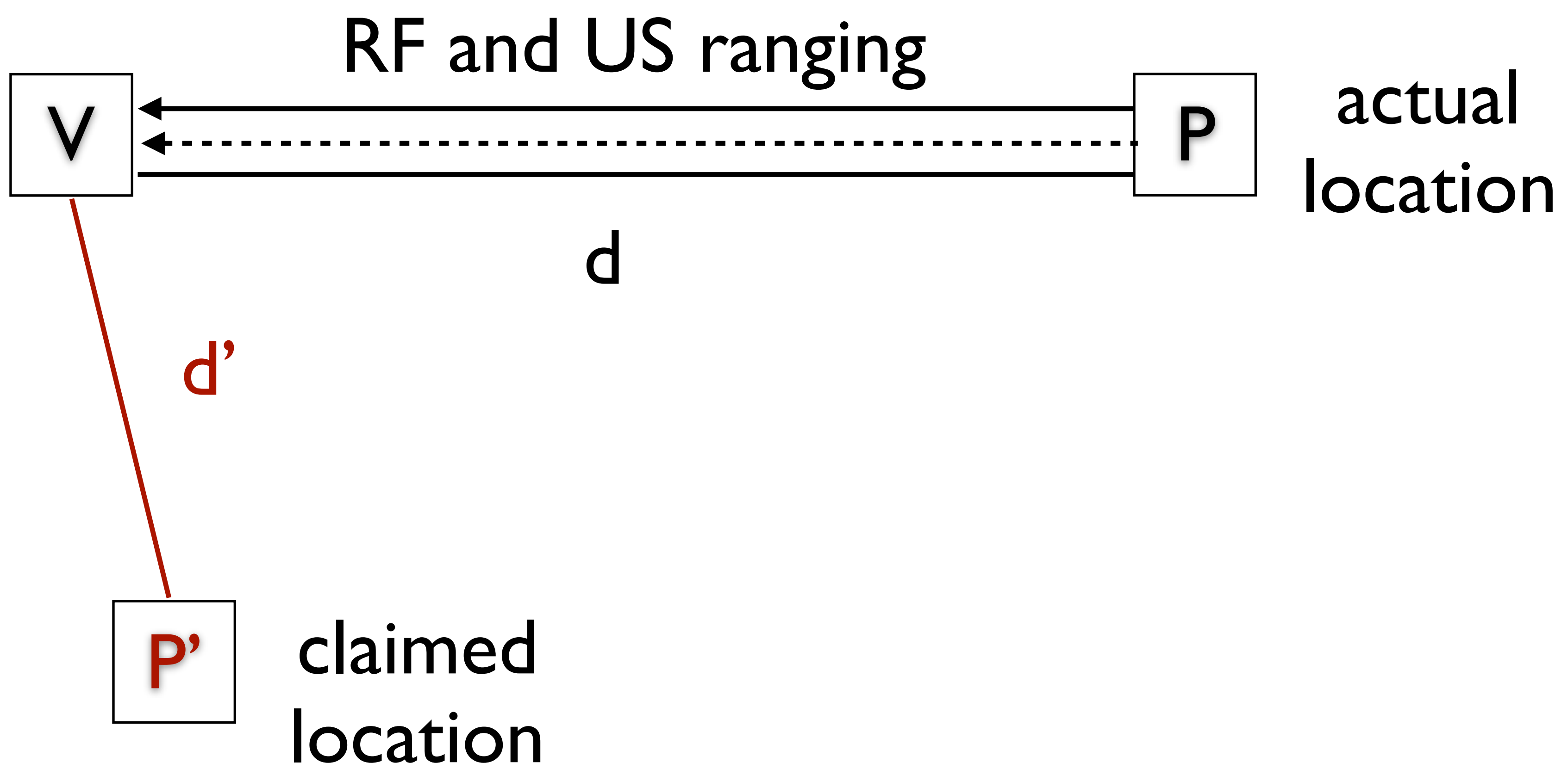

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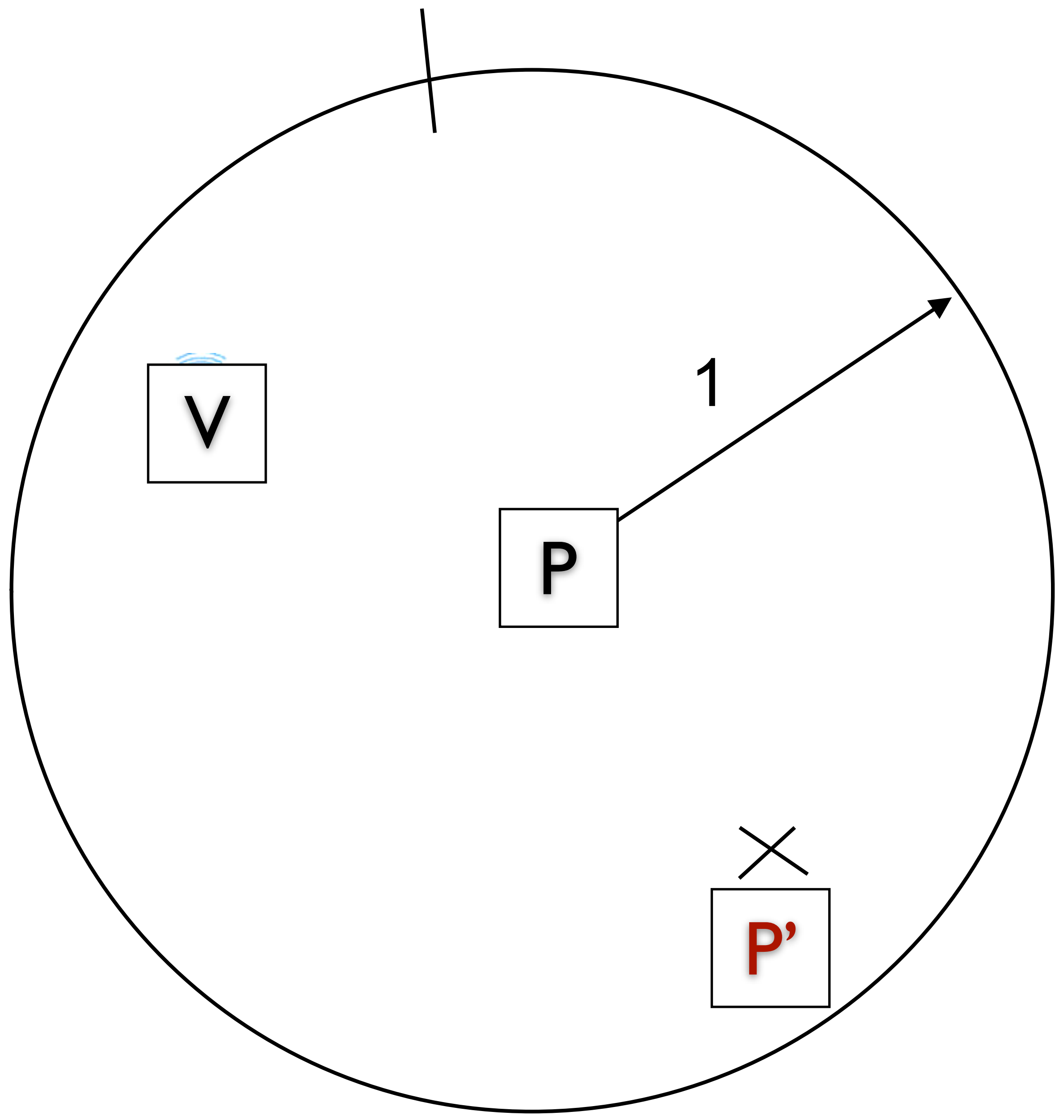
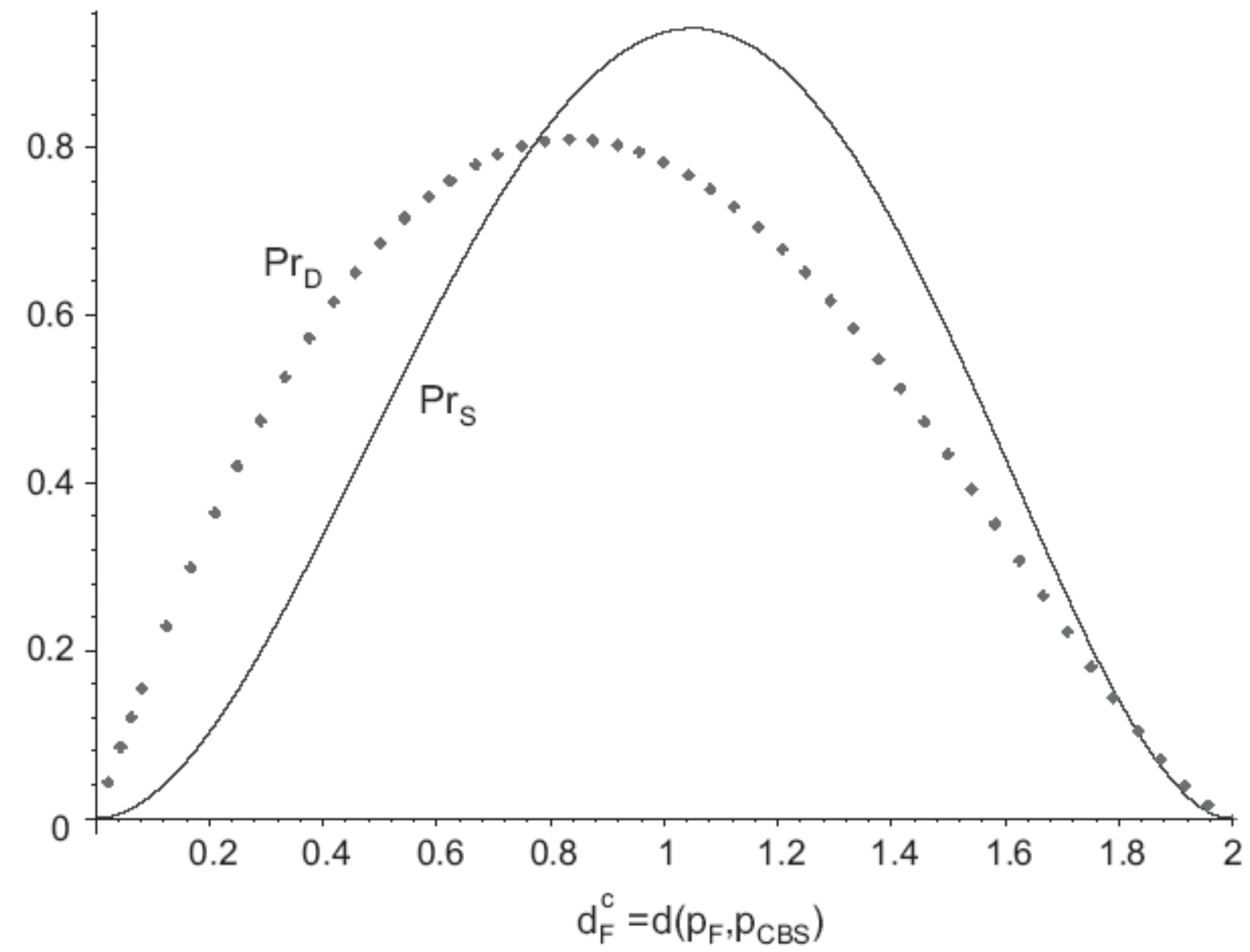


Observation 1:



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.*

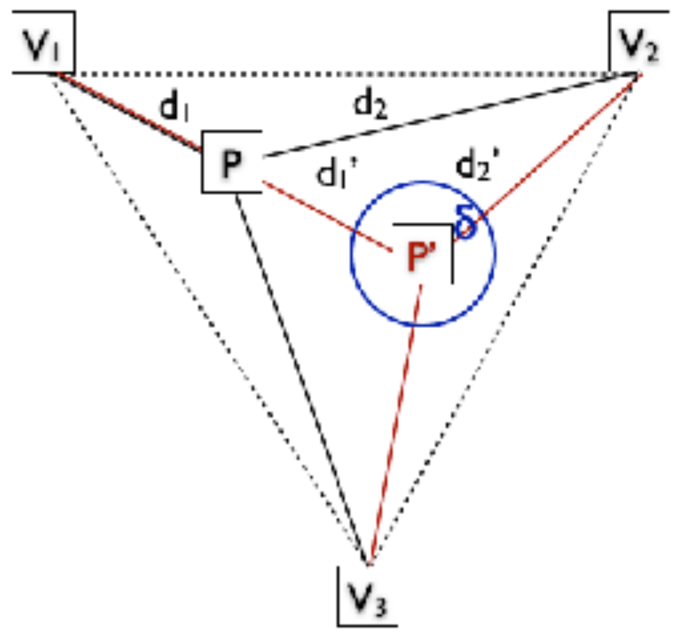
Summary (on secure localization)

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)

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, ...