Distance bounding overview

Distance bounding overview

- *Mafia fraud*: an adversary tricks a *verifier* into thinking that a *prover* is near, by establishing a *relay link* between them
- *Distance fraud*: the prover itself is malicious, and tricks the verifier into thinking to be near

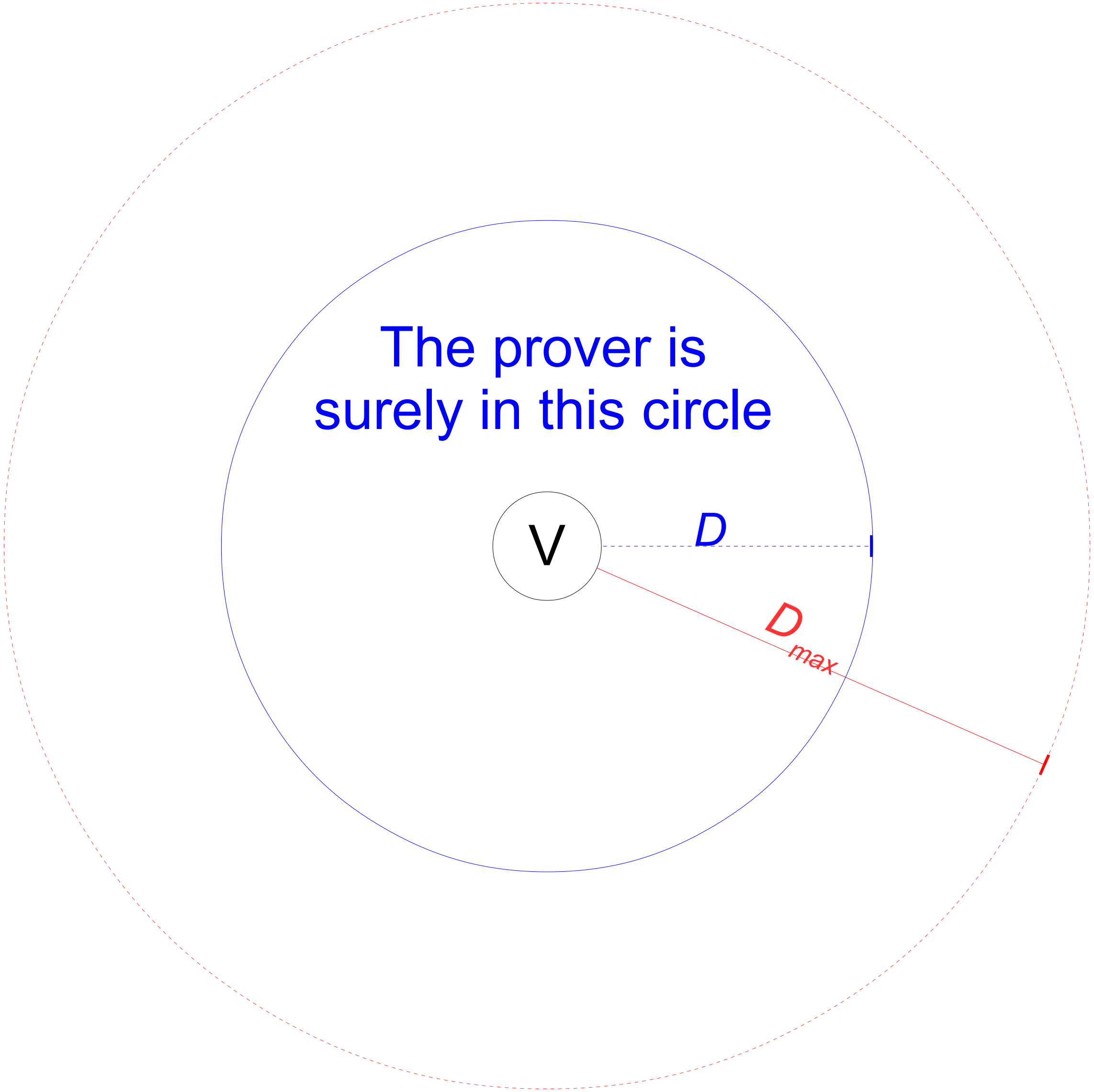
Distance bounding overview

- A *distance bounding protocol* permits us to establish a *secure upper bound* (*D*) to the distance between a “prover” and a “verifier”:

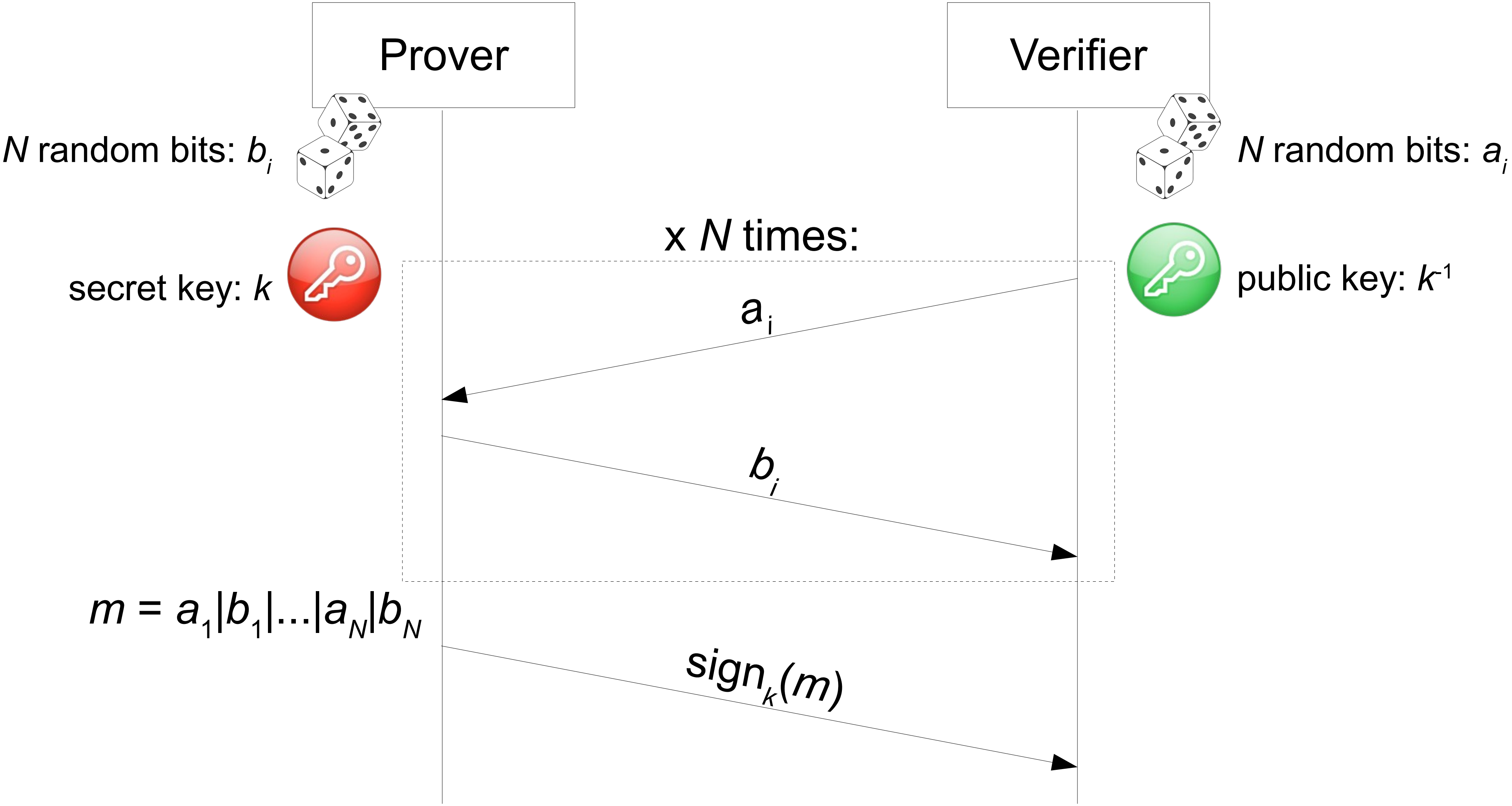
$$d <= D$$

- The basic idea is to precisely measure the *round-trip time* between two unpredictable messages (a challenge and a response)

Distance bounding overview



Brands-Chaum protocol (type I)



Prover

Verifier

N random bits: b_i

N random bits: a_i

secret key: k

public key: k^{-1}

x N times:

a_i

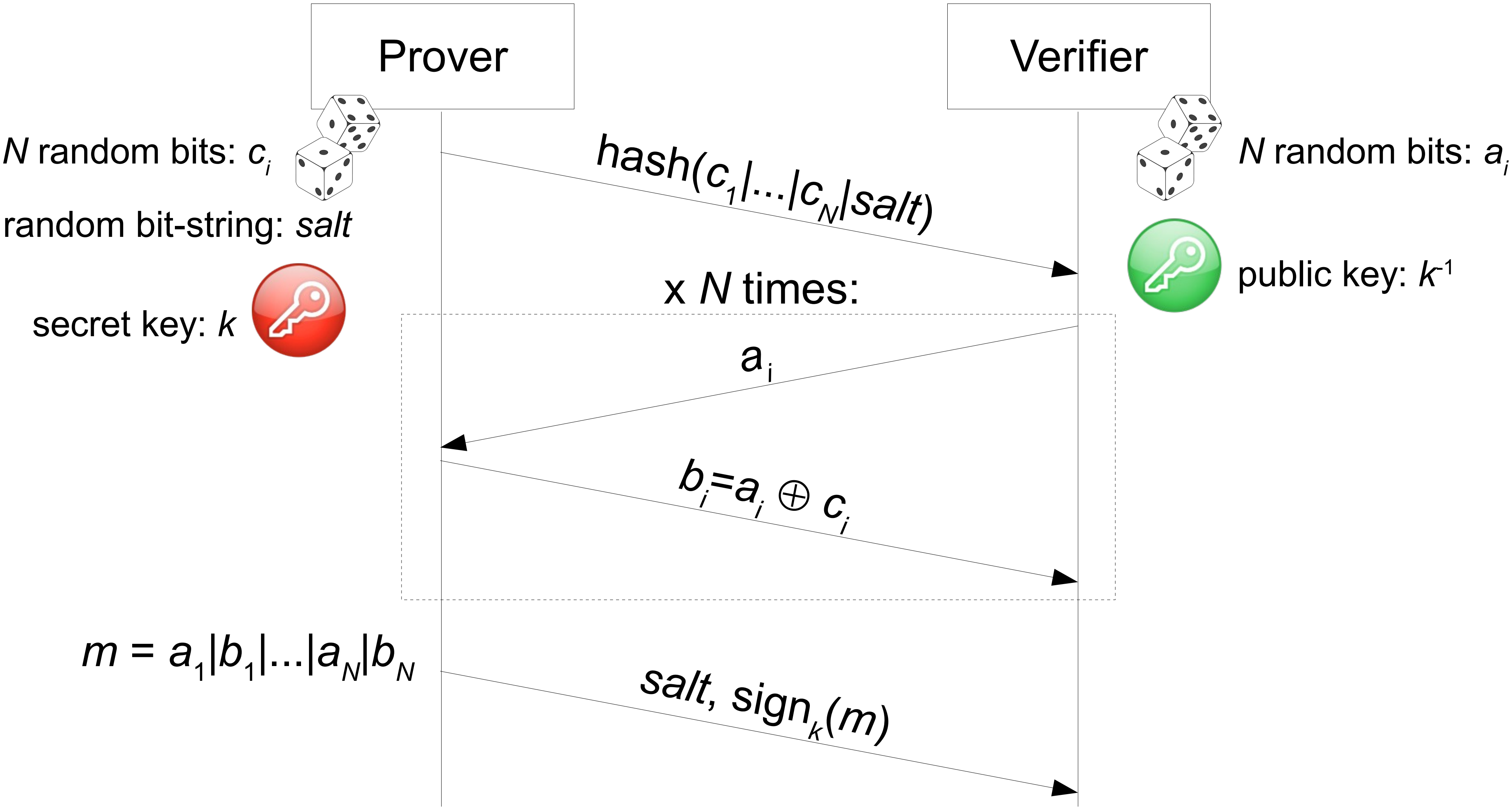
b_i

$m = a_1|b_1|\ldots|a_N|b_N$

$sign_k(m)$

It resists only against mafia fraud

Brands-Chaum protocol (type II)



Prover

Verifier

N random bits: c_i

random bit-string: *salt*

secret key: k

N random bits: a_i

public key: k^{-1}

$hash(c_1|\ldots|c_N|salt)$

x N times:

a_i

$b_i = a_i \oplus c_i$

$m = a_1|b_1|\ldots|a_N|b_N$

$salt, sign_k(m)$

It resists against both mafia fraud and distance fraud

Brands-Chaum protocols

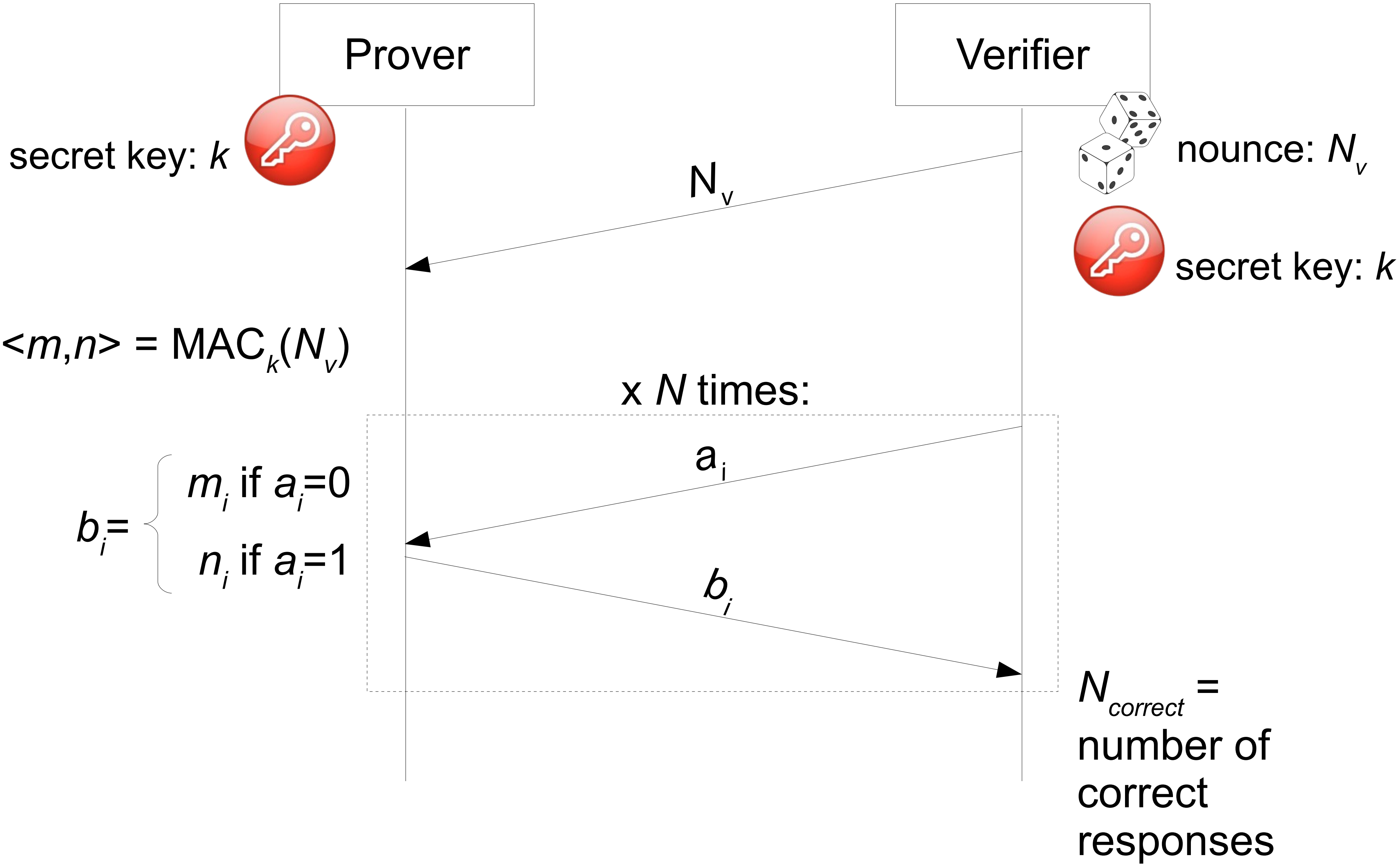
- Type I:
  - Adversarial success probability (mafia fraud):

$$P_{adv} = (1/2)^N$$

- Type II:
  - Adversarial success probability (mafia and distance frauds):

$$P_{adv} = (1/2)^N$$

Hancke-Kuhn protocol



Prover

Verifier

secret key: k

nounce: N_v

N_v

secret key: k

$\langle m,n \rangle = \mathrm{MAC}_k(N_v)$

x N times:

a_i

$$b_i = \begin{cases} m_i \text{ if } a_i=0 \\ n_i \text{ if } a_i=1 \end{cases}$$

b_i

$N_{correct}$ = number of correct responses

It resists against both mafia fraud and distance fraud

Hancke-Kuhn protocol

- Adversarial success probability (mafia fraud):
  - Double-chance guessing attack
  - Overclocking attack

$$P_{adv} = \sum_{i=N_{accept}}^{N} \binom{N}{i} (3/4)^i (1/4)^{N-i}$$

- Adversarial success probability (distance fraud):

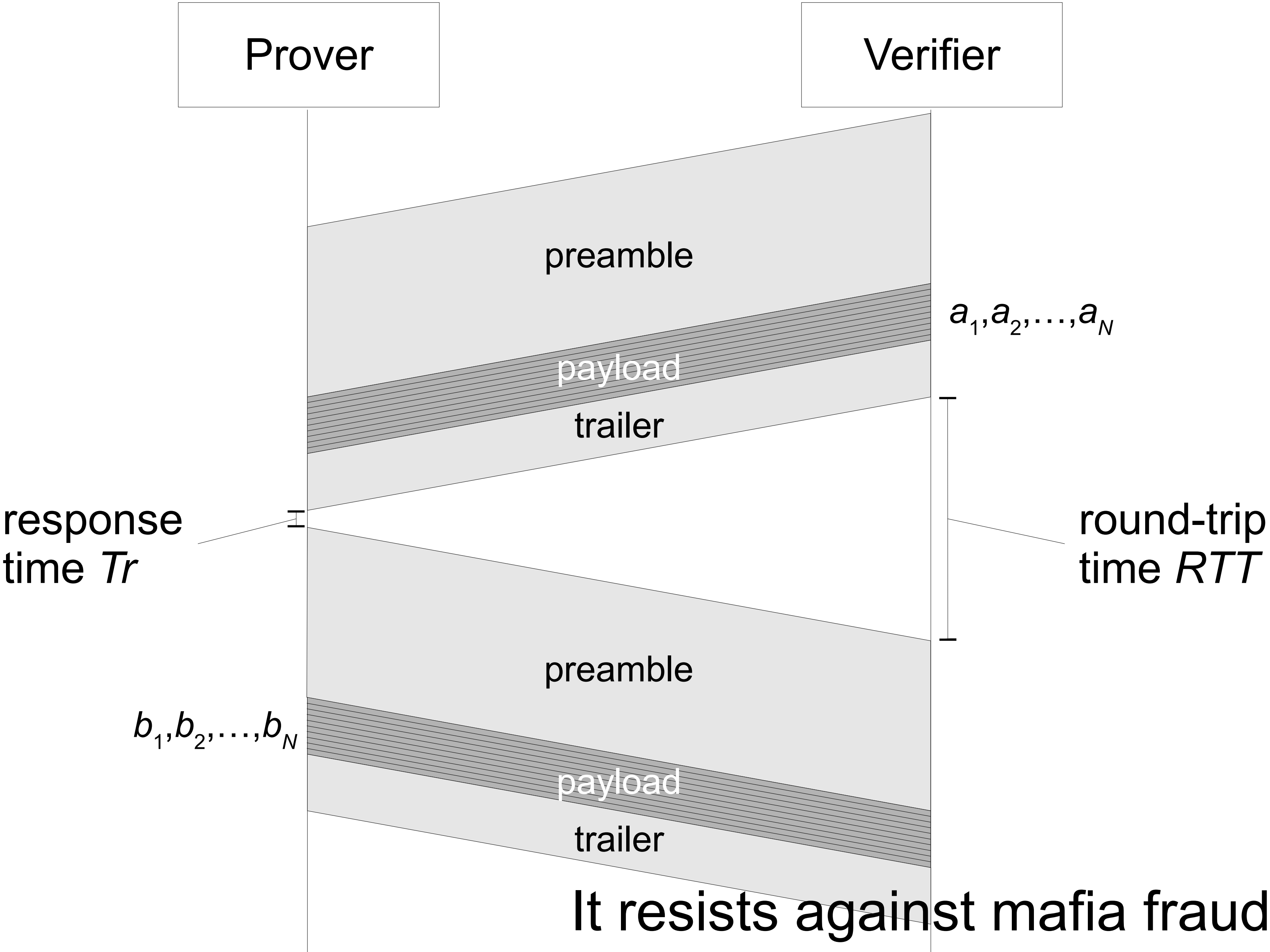
$$P_{adv} = \sum_{i=N_{accept}}^{N} \binom{N}{i} (3/4)^i (1/4)^{N-i}$$

- With N=128 and N_{accept}=124: P_{adv} = 10^{-12}

Frame-based distance bounding

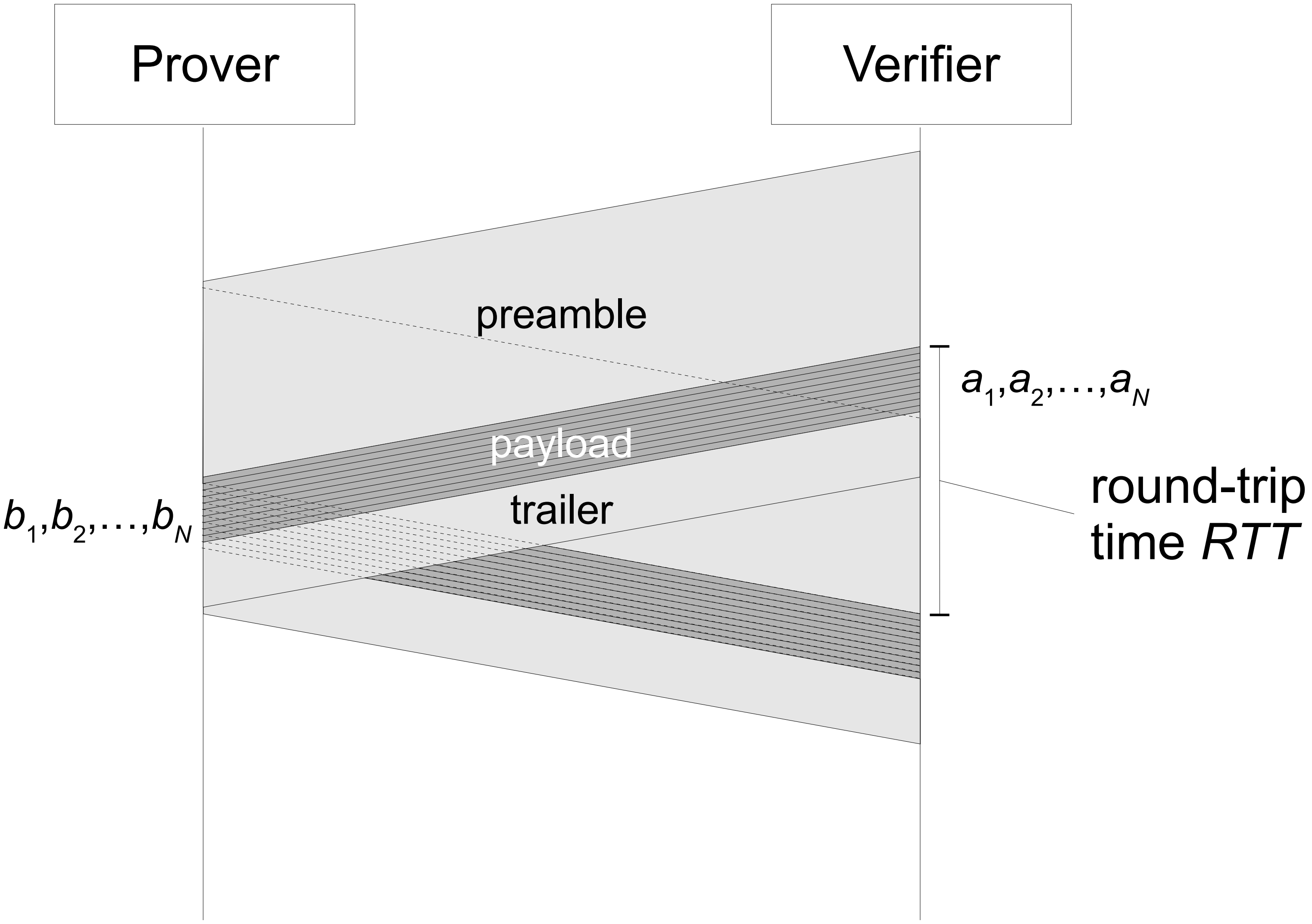
- Medium range communication (20-30 meters): we cannot send single bits
- We use the same protocols (Brands-Chaum, Hancke-Kuhn)
- Instead of performing N single-bit rounds, we perform a single round with an N-bit frame

Frame-based distance bounding



It resists against mafia fraud only

Frame-based distance bounding



It resists against both mafia fraud and distance fraud

Distance bounding implementation

2009

Secure positioning

Problem type

- *Secure positioning* (properly said): to securely measure the position of a device
- *Secure position verification*: to verify that a (previously measured) position is actually true

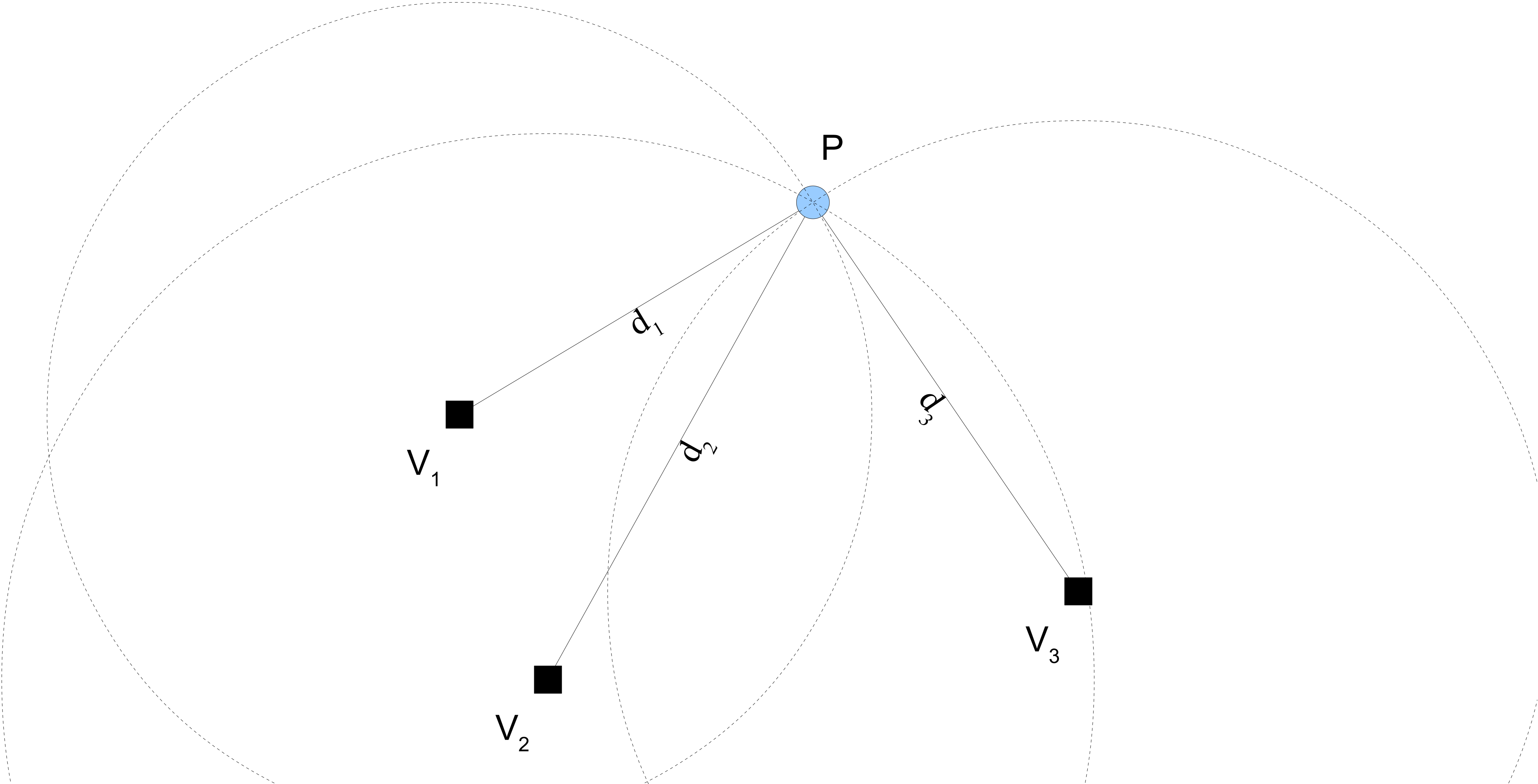
Positioning method types

- *Range-dependent*: based on the *ranging operation* (the measurement of a distance)
  - Very precise
  - Expensive (dedicated hardware for ranging)
- *Range-independent*: based on higher-level information (signal strength, beacon reception, etc.)
  - Poorly precise
  - Cheap (no dedicated hardware)

Multilateration

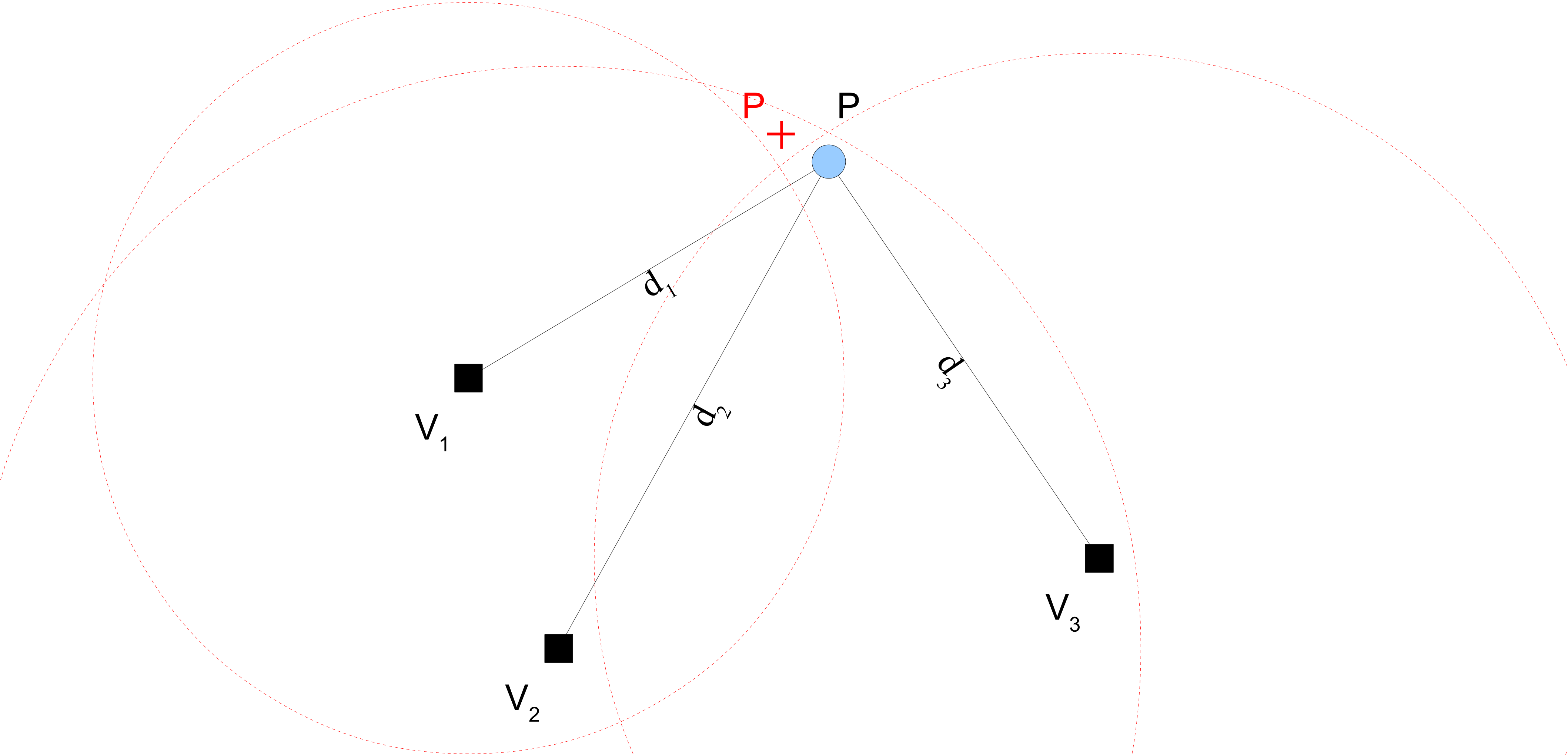
- Range-based positioning method
- Based on the measurement of 3 (or more) distances from the *target node* to 3 (or more) anchor nodes

Multilateration



Multilateration

- In presence of ranging errors: *least-squared-error solution* (LSE)



Multilateration

- d_i is the distance from anchor node V_i
- d'_i is the measured distance from V_i
- X_P is the position of the target node
- X'_P is the measured position of the target node

Multilateration

- Without ranging error (exact solution):

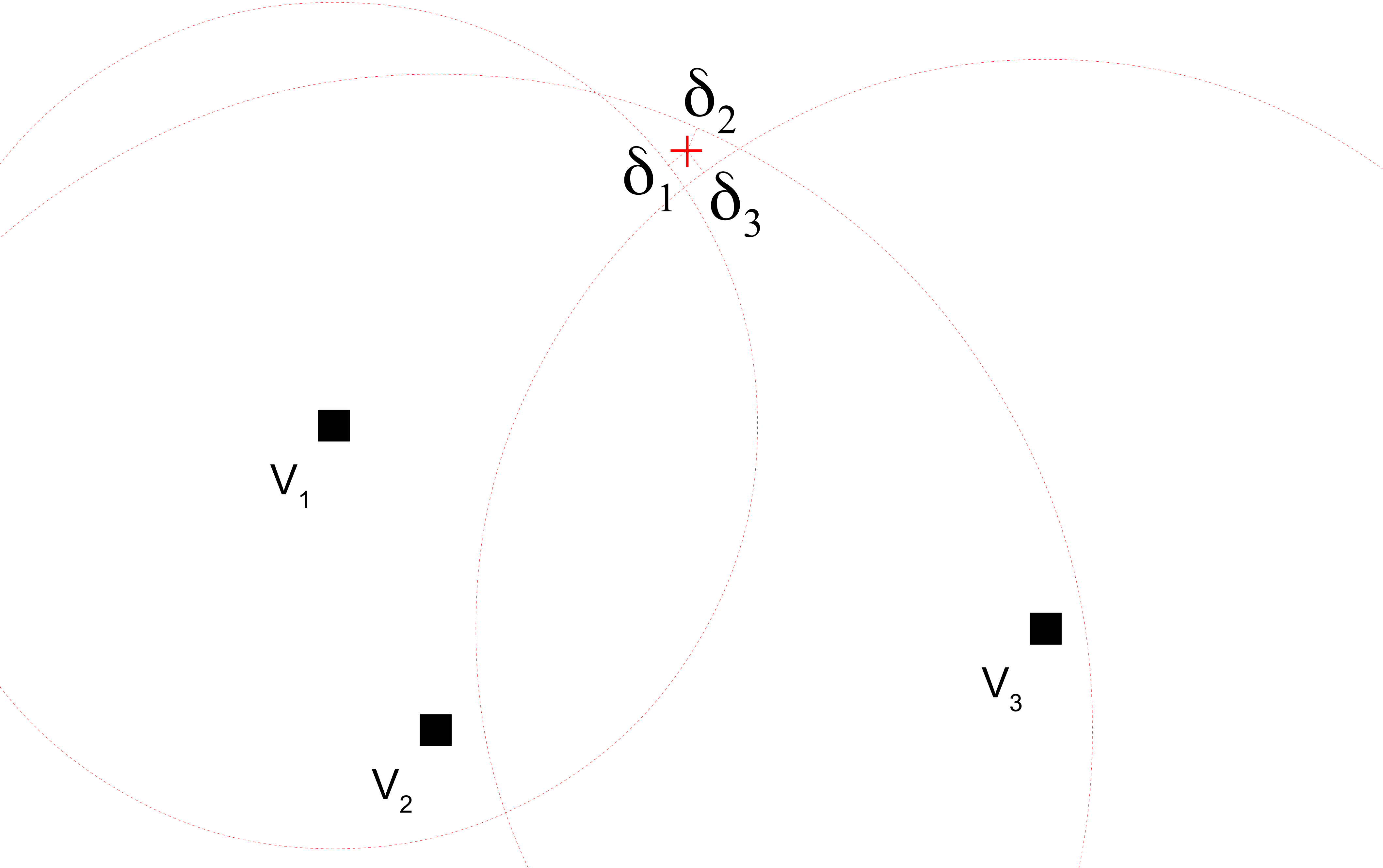
$$\begin{cases} \left|X_{V_1} - X_P'\right| = d_1' \\ \left|X_{V_2} - X_P'\right| = d_2' \\ \left|X_{V_3} - X_P'\right| = d_3' \end{cases}$$

- With ranging error (least-squared-error solution)

$$\begin{cases} \min \sum_i \delta_i^2 \\ \left|X_{V_1} - X_P'\right| - d_1' = \delta_1 \\ \left|X_{V_2} - X_P'\right| - d_2' = \delta_2 \\ \left|X_{V_3} - X_P'\right| - d_3' = \delta_3 \end{cases}$$

residuals

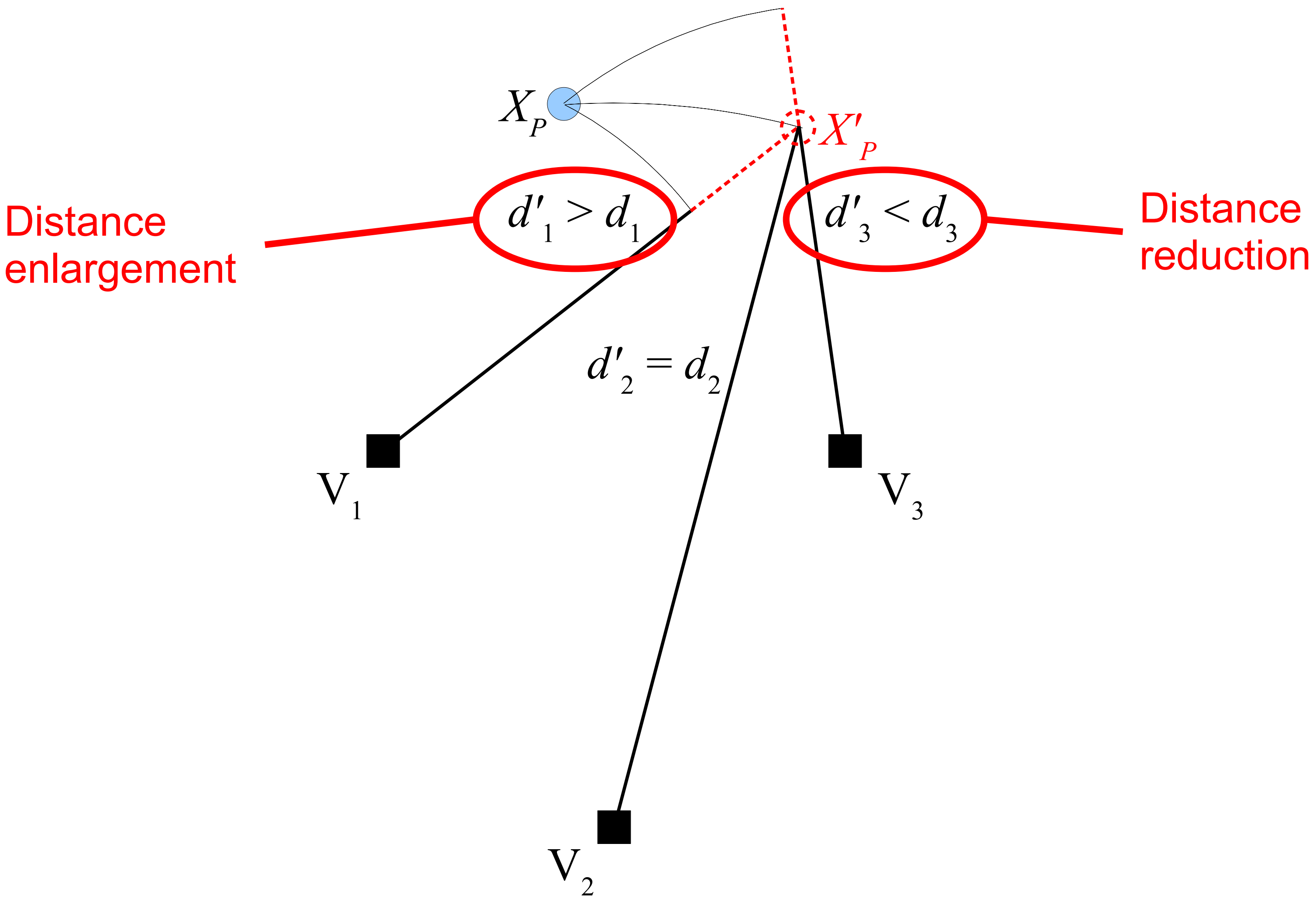
Multilateration



Multilateration

- The residuals give an indirect estimation of the positioning imprecision
- If the residuals are high, the positioning is imprecise (the contrary could not be true)

Multilateration spoofing



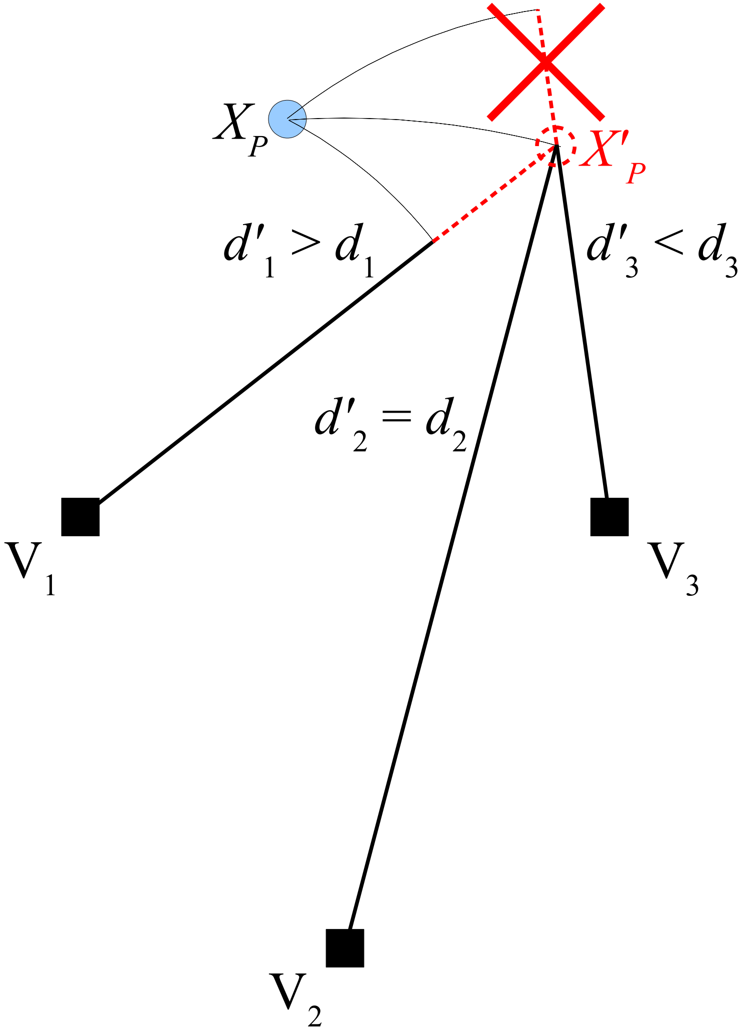
Distance enlargement

Distance reduction

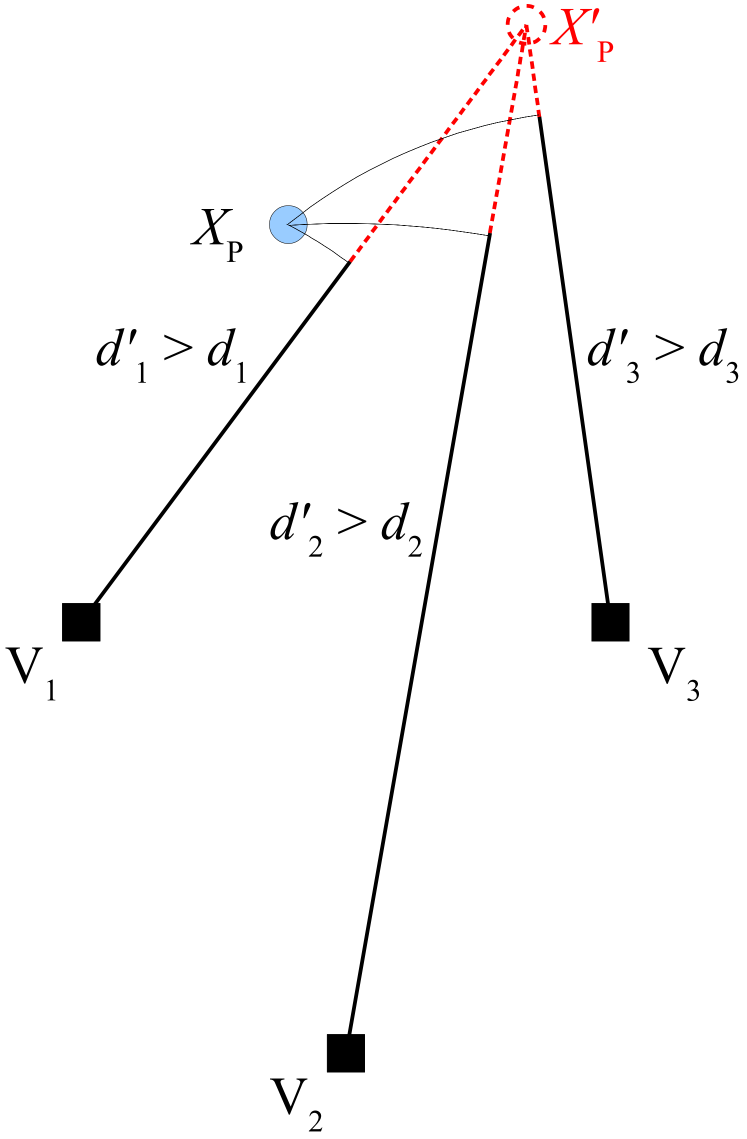
Verifiable multilateration

- *Idea*: perform ranging operations via wireless distance bounding protocols
- Distance reduction is *impossible*
- Distance enlargement is still possible
  - *Jam-replay* (jamming a response and replaying it)
  - *Overshadow* (replaying a response with much more power)

Verifiable multilateration

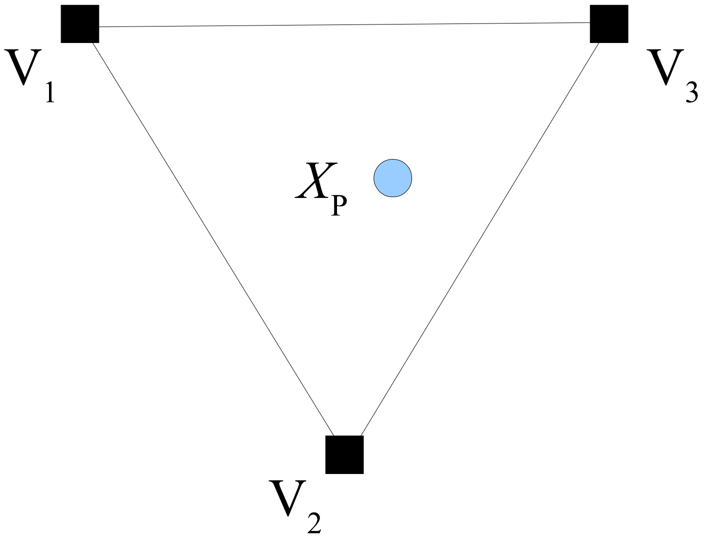


Verifiable multilateration



Verifiable multilateration

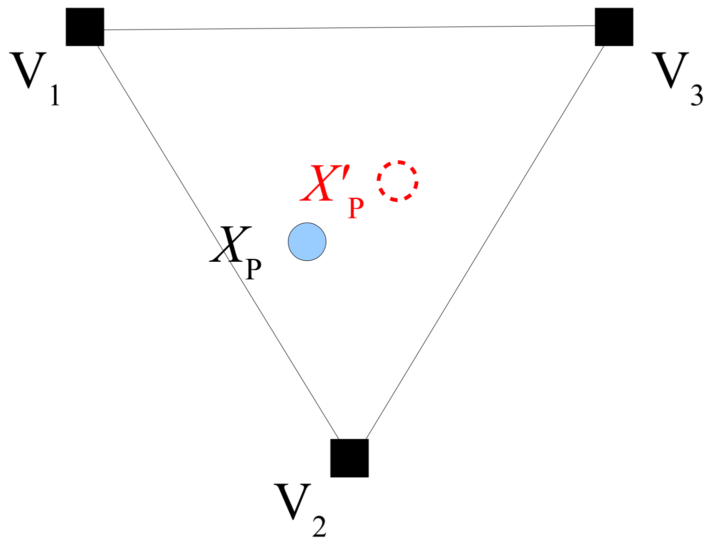
- Accept a position only if it is inside the polygon formed by the anchor nodes (*in-polygon test*)



- Spoofing a position inside the polygon *always* requires a distance reduction

Verifiable multilateration

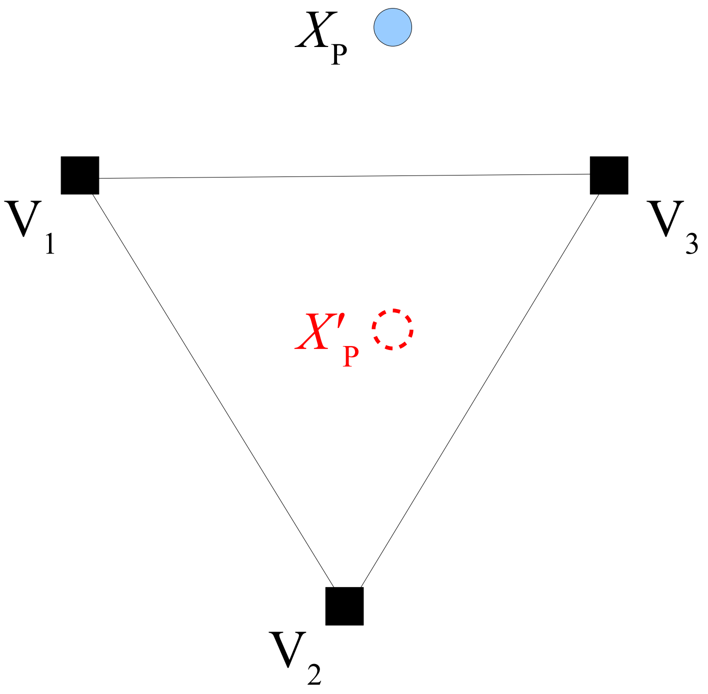
- Case of “inside-inside” spoofing



- Distance reduction against V_3 (impossible)

Verifiable multilateration

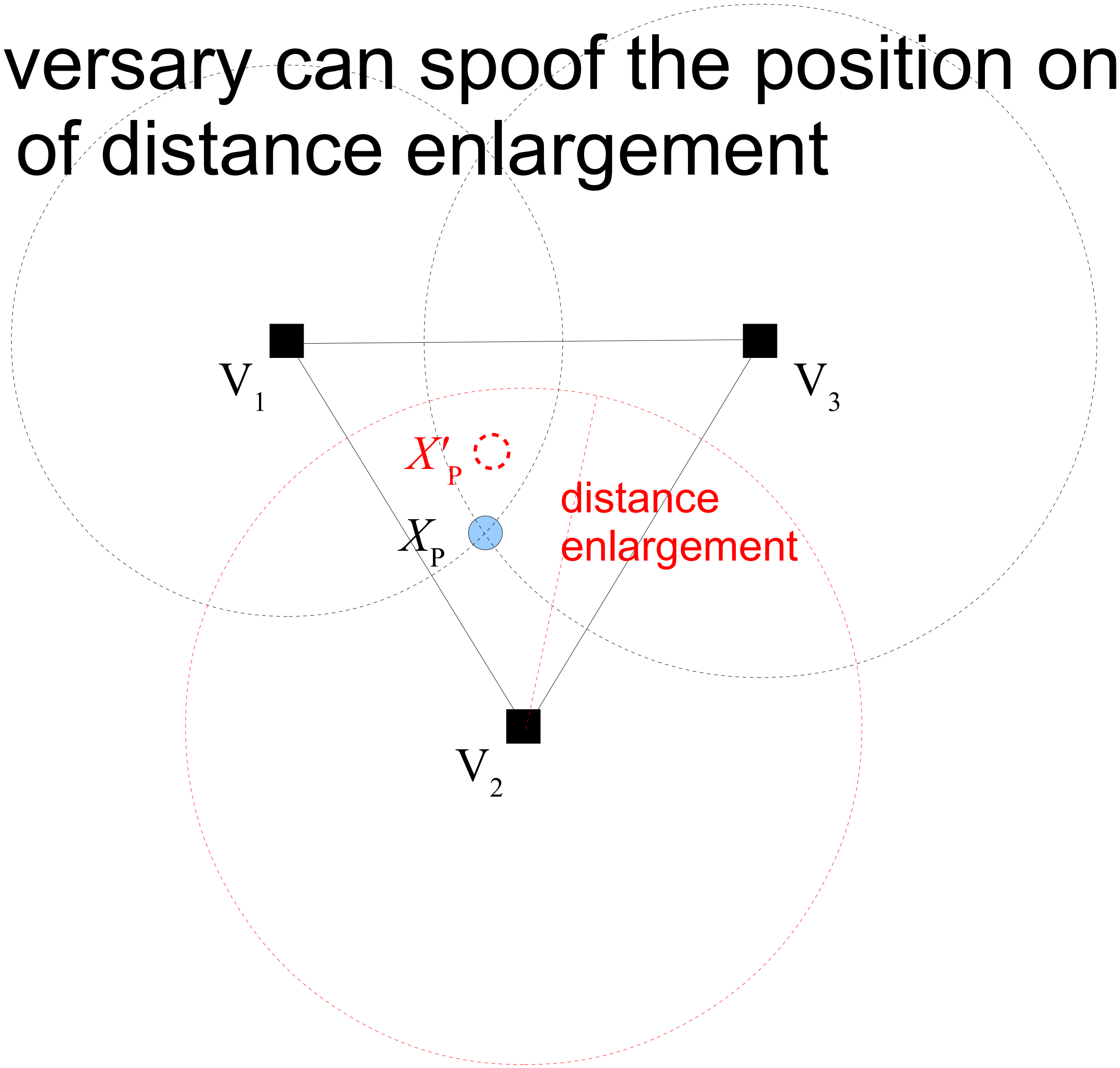
- Case of “outside-inside” spoofing



- Distance reduction against V_2 (impossible)

Verifiable multilateration

- The adversary can spoof the position only by means of distance enlargement



Verifiable multilateration

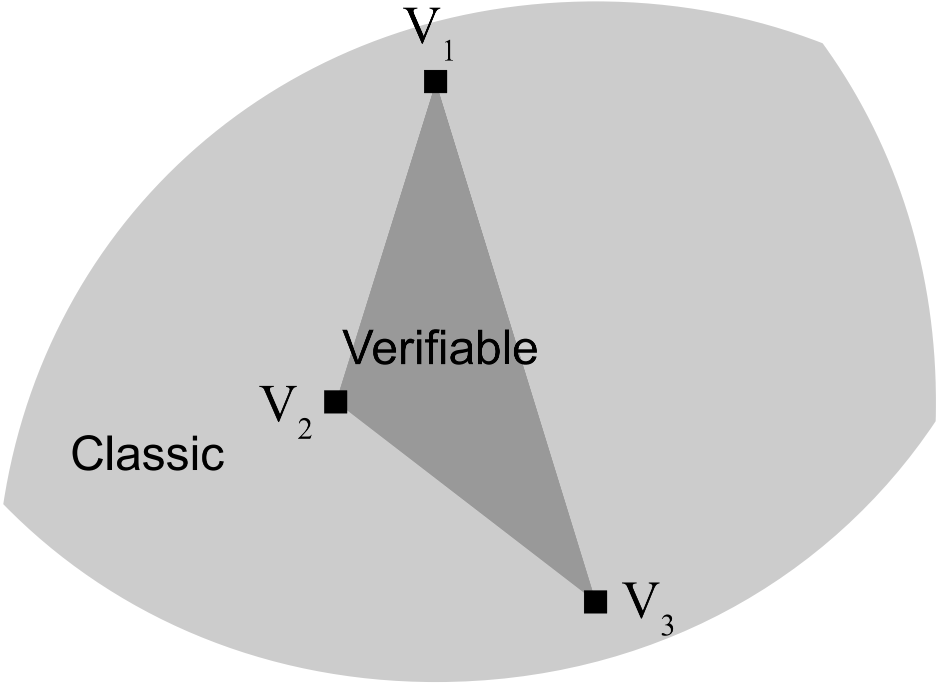
- Accept a position only if it produced low residuals (δ-*test*)

Verifiable multilateration

- Complete algorithm:
  1. Determine the list of anchor nodes inside the power range of the target
  2. For each anchor node, perform distance bounding
  3. Compute the position by means of least-squared-error problem
  4. If one residual is greater than a threshold δ_{max}, then reject the position (δ*-test*)
  5. If the position is not inside the polygon of the anchor nodes, reject the position (*in-polygon test*)
  6. Otherwise, accept the position

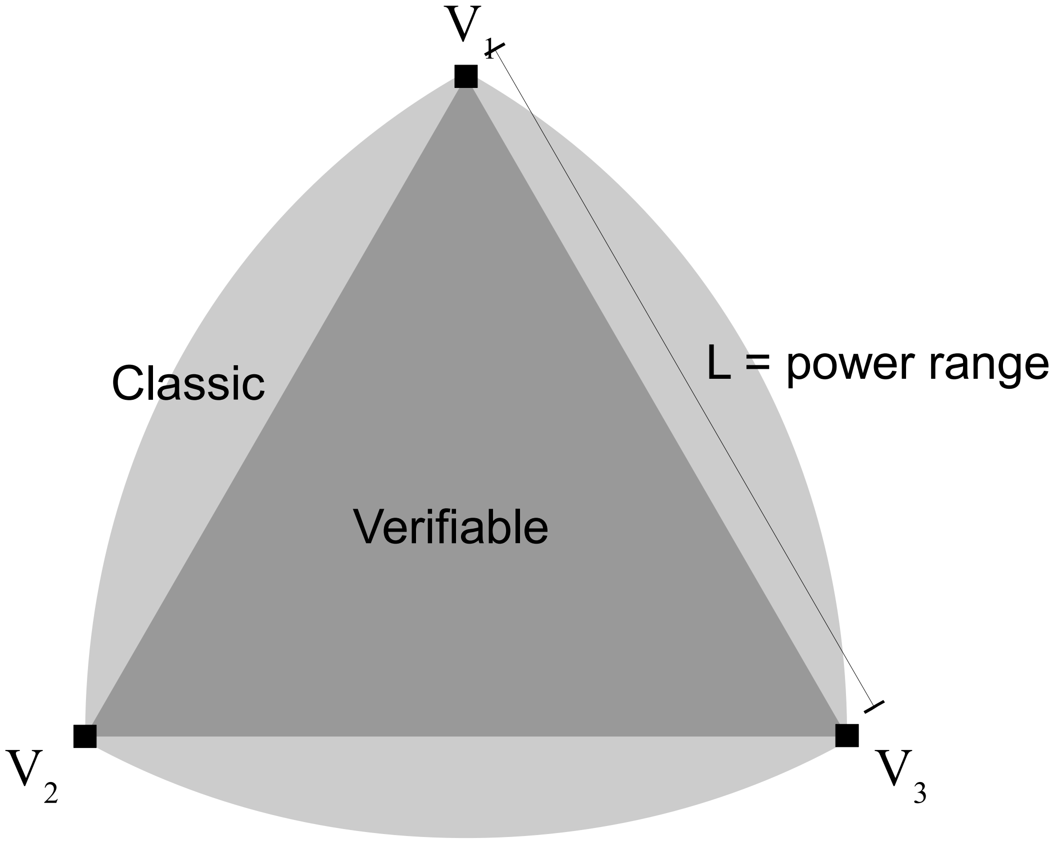
Coverage

- The coverage area is smaller than (classic) multilateration



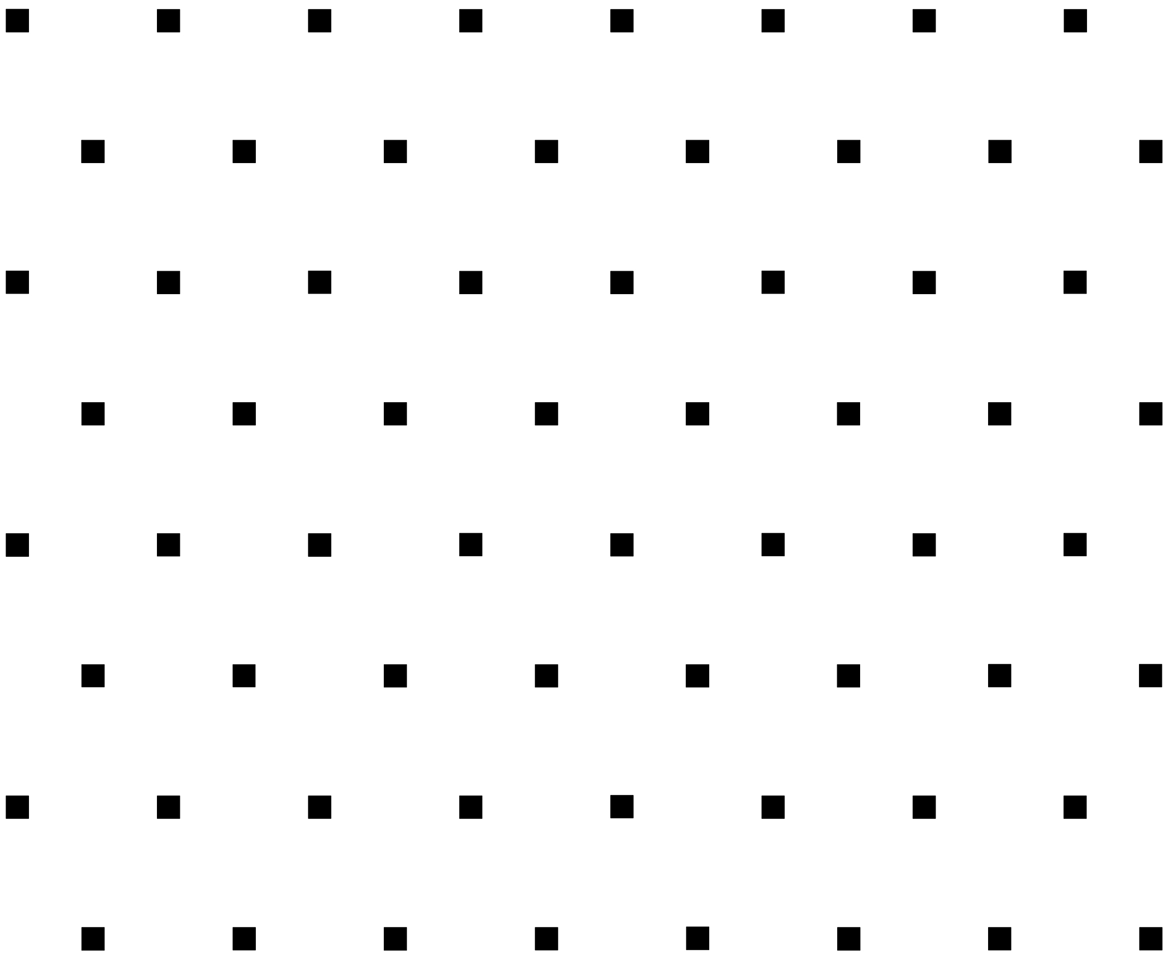
Coverage

- Best way to deploy anchor nodes (*hive deployment*)



Coverage

- Best way to deploy anchor nodes (*hive deployment*)



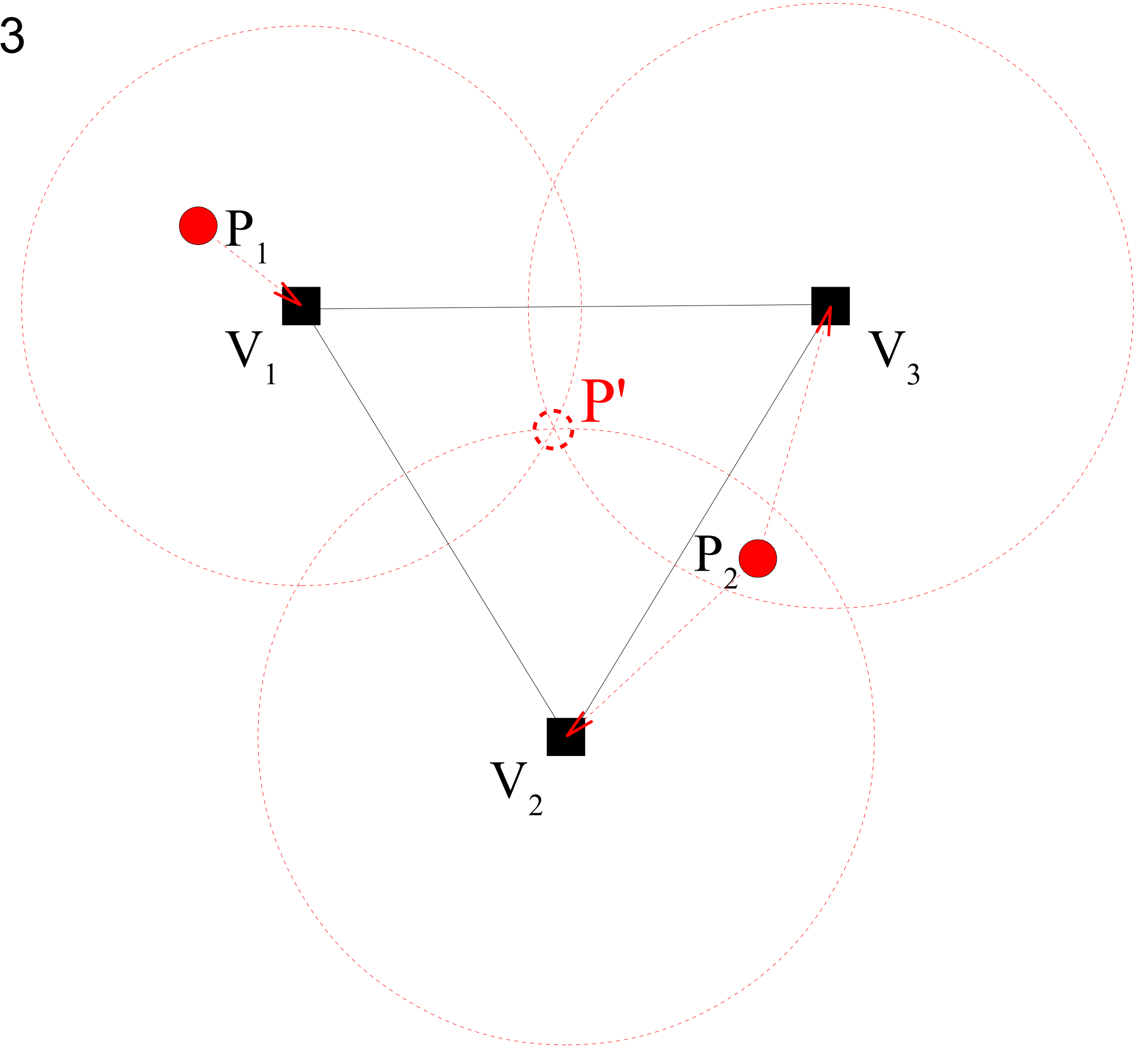
Repeat the scheme

Security analysis

- Verifiable multilateration has the same security level of the employed distance bounding
- Case of *external adversary*: use a distance bounding resistant against mafia fraud (e.g. Brands-Chaum type I)
- Case of (single) *dishonest target node*: use a distance bounding resistant against mafia and distance frauds (e.g. Hancke-Kuhn)
- Case of *multiple* dishonest target nodes?

Colluding-internals attack

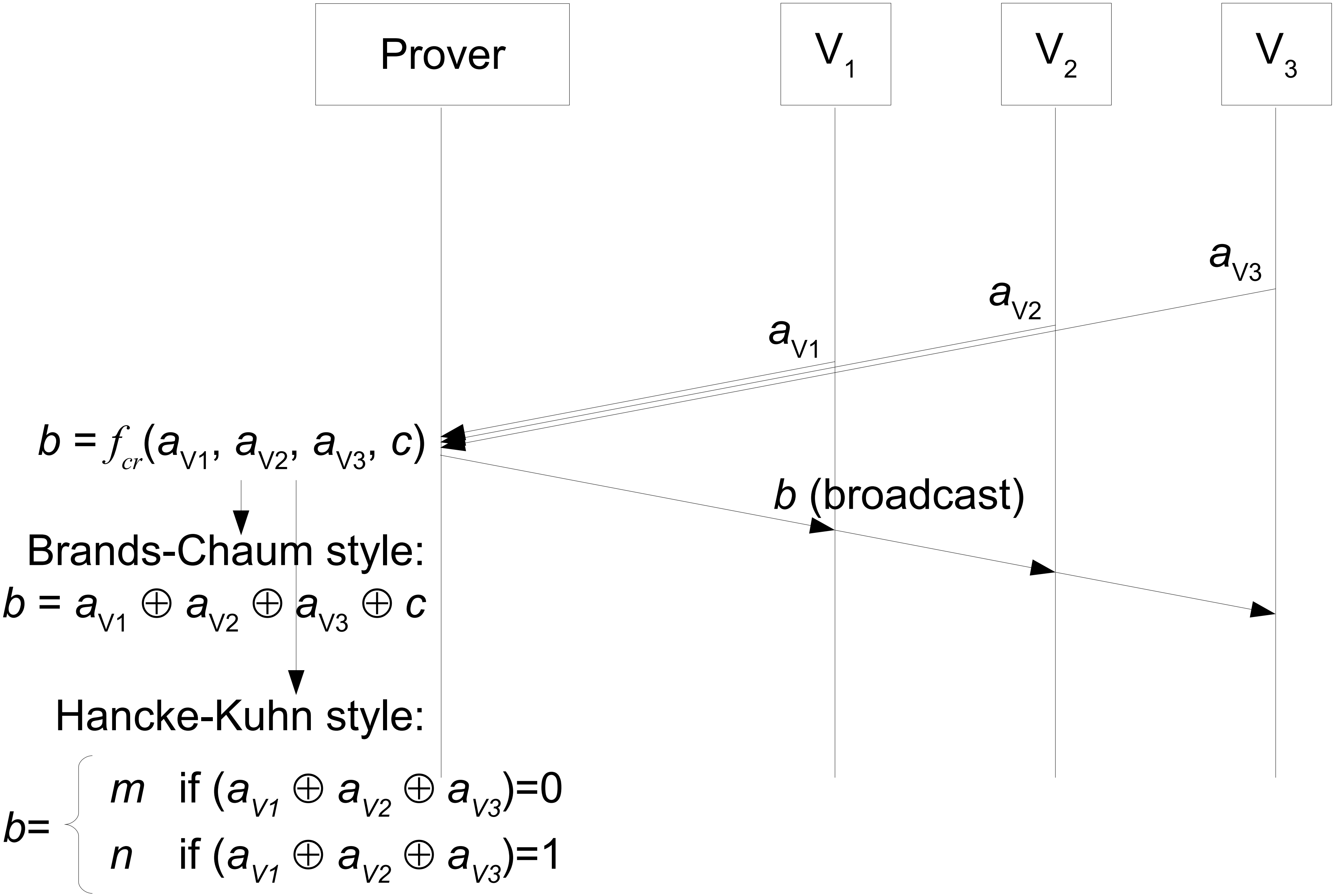
- P_2 attacks V_2 and V_3
- P_1 attacks V_1
- Verifiable multilateration does not resist against colluding dishonest targets



Simultaneous verifiable multilateration

- Instead of *N* distance boundings: a single *intertwined* distance bounding
- Intertwined distance bounding: multi-party distance bounding (1 prover, *N* verifiers)
  - A challenge for each verifier
  - The challenges arrive simultaneously to the prover (*N* wireless channels)
  - A single (broadcast) response from the prover
  - The response depends on all the challenges

Intertwined distance bounding



Prover

V_1

V_2

V_3

a_{V3}

a_{V2}

a_{V1}

$b = f_{cr}(a_{V1}, a_{V2}, a_{V3}, c)$

b (broadcast)

Brands-Chaum style:

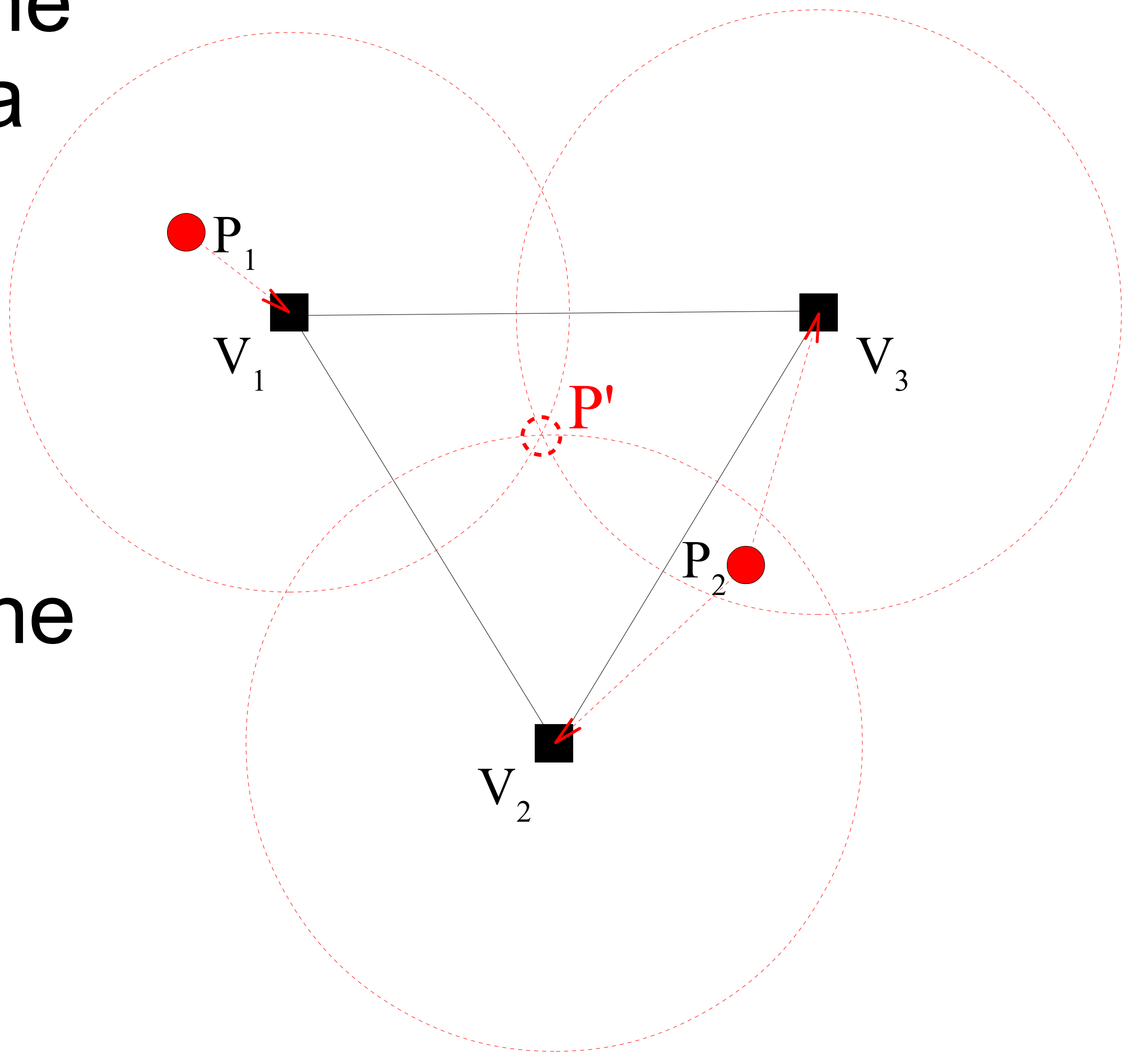
$b = a_{V1} \oplus a_{V2} \oplus a_{V3} \oplus c$

Hancke-Kuhn style:

$$b = \begin{cases} m & \text{if } (a_{V1} \oplus a_{V2} \oplus a_{V3}) = 0 \\ n & \text{if } (a_{V1} \oplus a_{V2} \oplus a_{V3}) = 1 \end{cases}$$

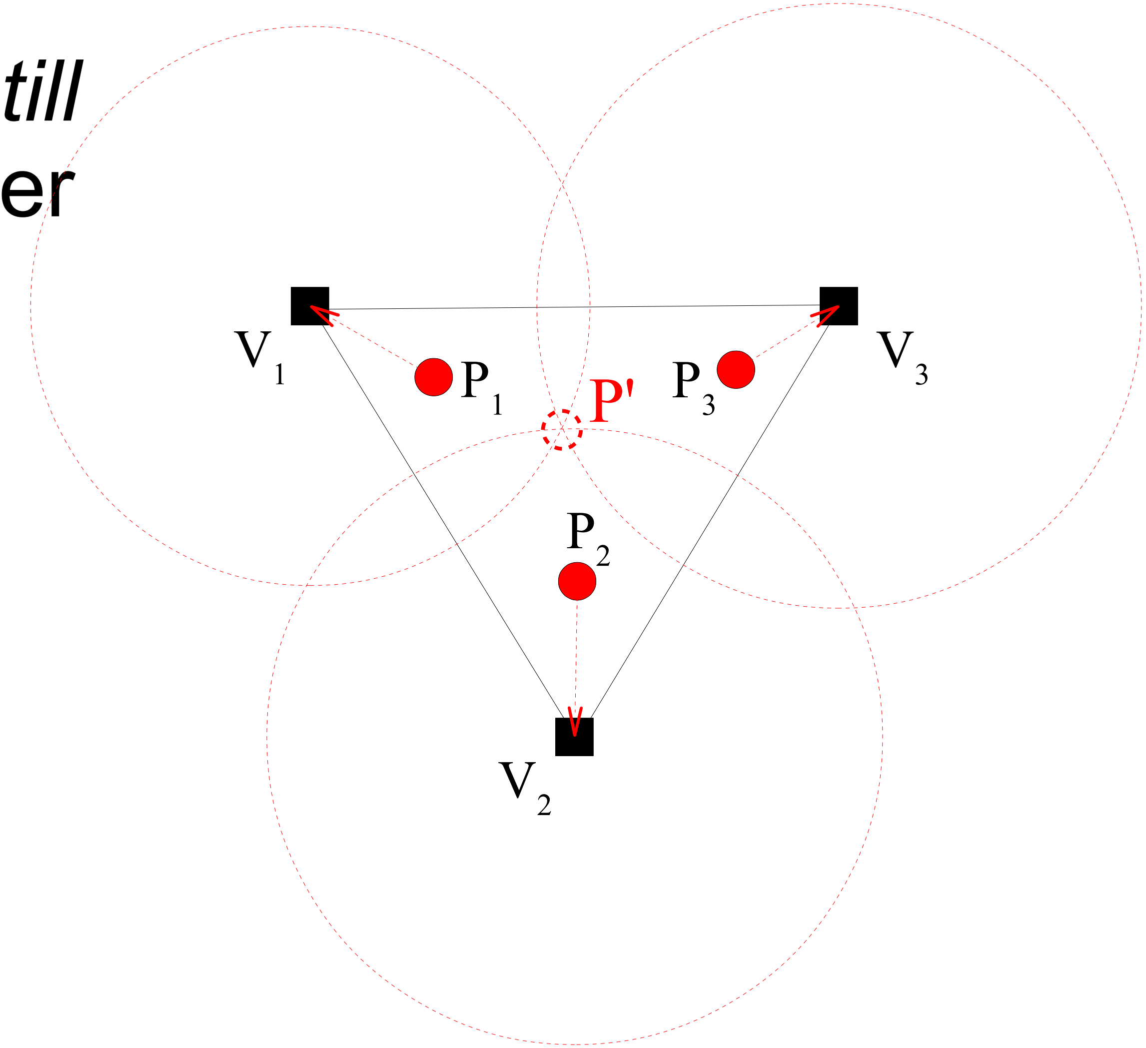
Security analysis

- The verifiers send the challenges in such a way they arrive contemporaneously at the *supposed position* P'
- P_2 cannot perform the enlargements, because he didn't receive the V_1's challenge yet



Security analysis

- The colluding internals attack is *still possible*, but in fewer situations
- It generally needs more colluders



Security analysis

- Simultaneous verifiable multilateration only *mitigates* the colluding-internals attack
- *Theorem (Chandran-Goyal-Moriarty-Ostrovsky)*: if the number of colluders is equal to (or greater than) the number of verifiers, no time-of-flight positioning is secure

Requirements for the intertwined distance bounding

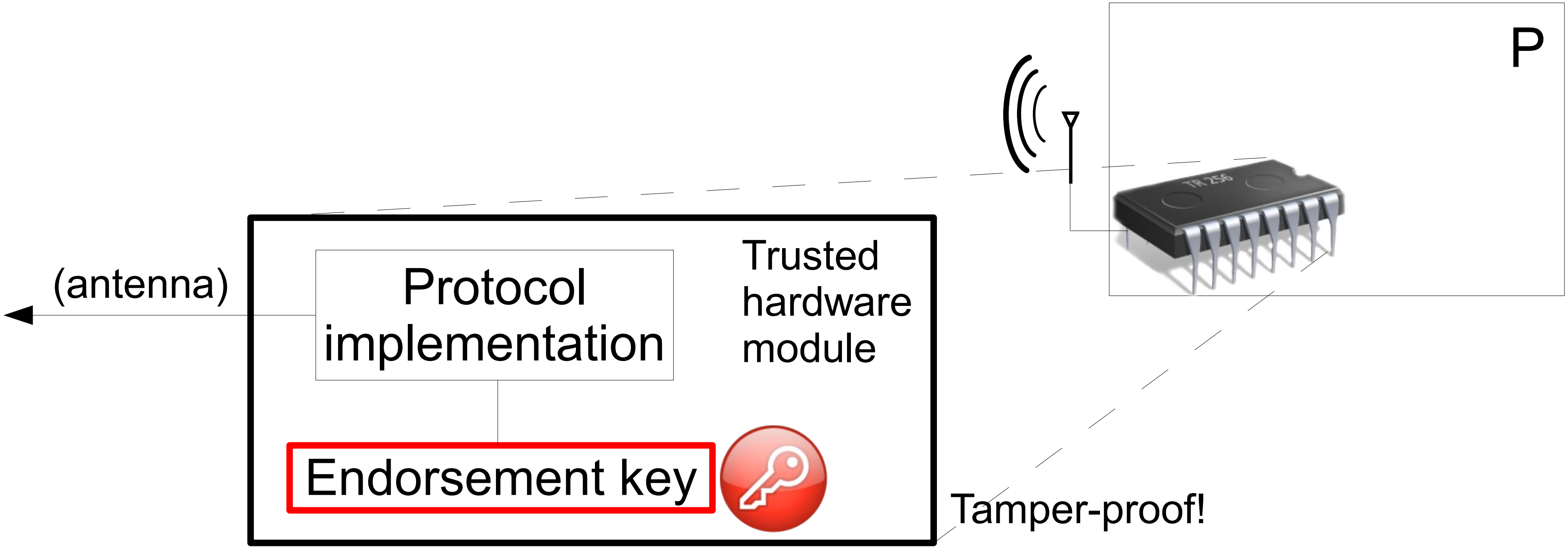
- The system must already know a *supposed position* P' (secure position verification)
  - The target itself declares it
  - Or it can be measured with an insecure method (like classic multilateration or GPS)
- The anchor nodes must be perfectly synchronized (with nanosecond precision)
  - Synchronization via *cable*: quite expensive
  - Synchronization via *wireless*: possibly insecure (an adversary can attack the synchronization protocol)

Trusted-hardware distance bounding

- An alternative way to avoid dishonest provers is to use *trusted hardware* for implementing distance bounding
- The correct execution of the protocol is assured by the trusted hardware
- A prover (or a set of colluding provers) *cannot act dishonestly*
- We can use simpler distance bounding protocols, like Brands-Chaum type I (no distance fraud is possible)

Trusted-hardware distance bounding

- The protocol is implemented in hardware



- The key (*endorsement key*) is created at manufacture time and stored in hardware
- Nobody knows the key except for the trusted hardware module

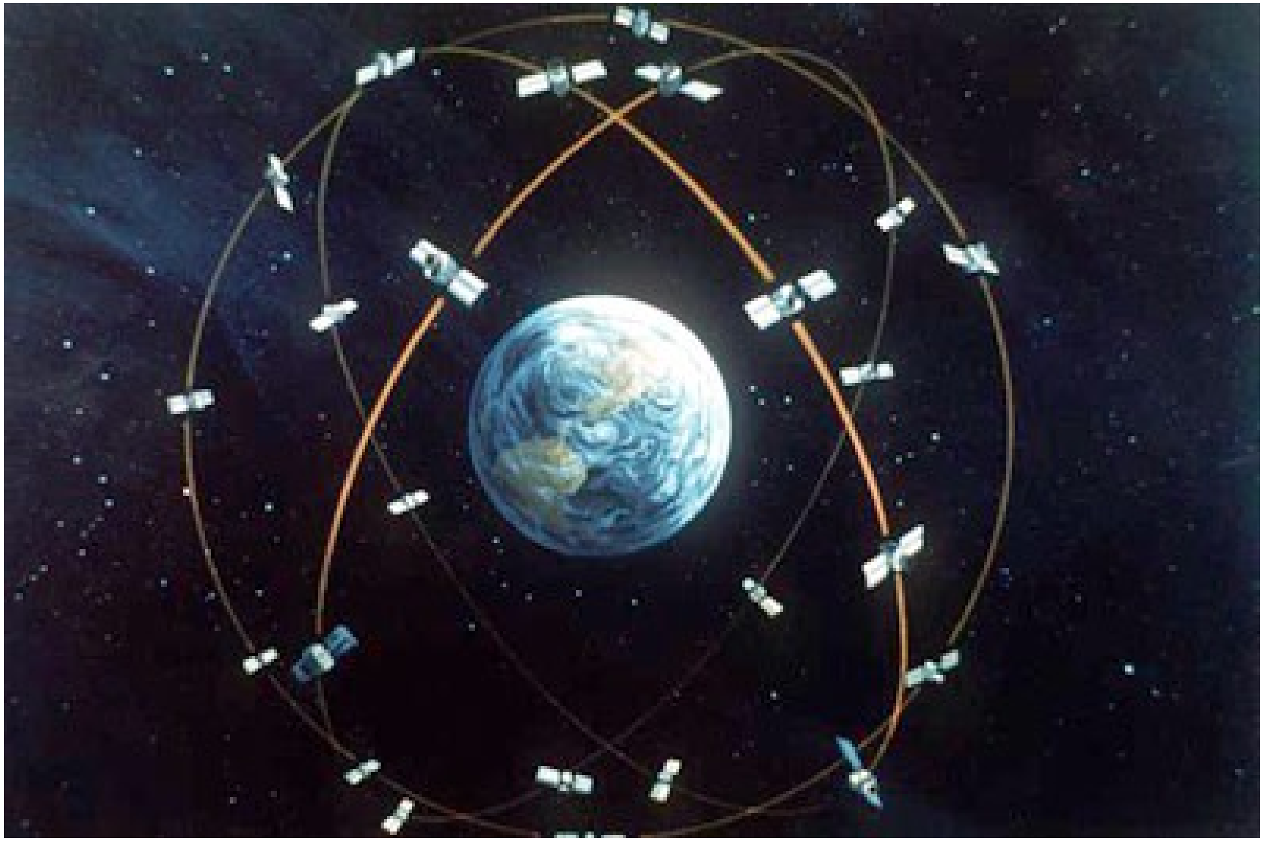
SeRLoc

- Secure Range-independent Localization
- Nodes are *not* equipped with ranging hardware (cheaper)
- Target nodes are *trusted*, they determine their own position
- The anchor nodes periodically send authenticated beacon packets
- Target nodes determine their own position by listening to the beacon packets

SeRLoc

- The beacon packets are protected against jamming and

Secure GPS

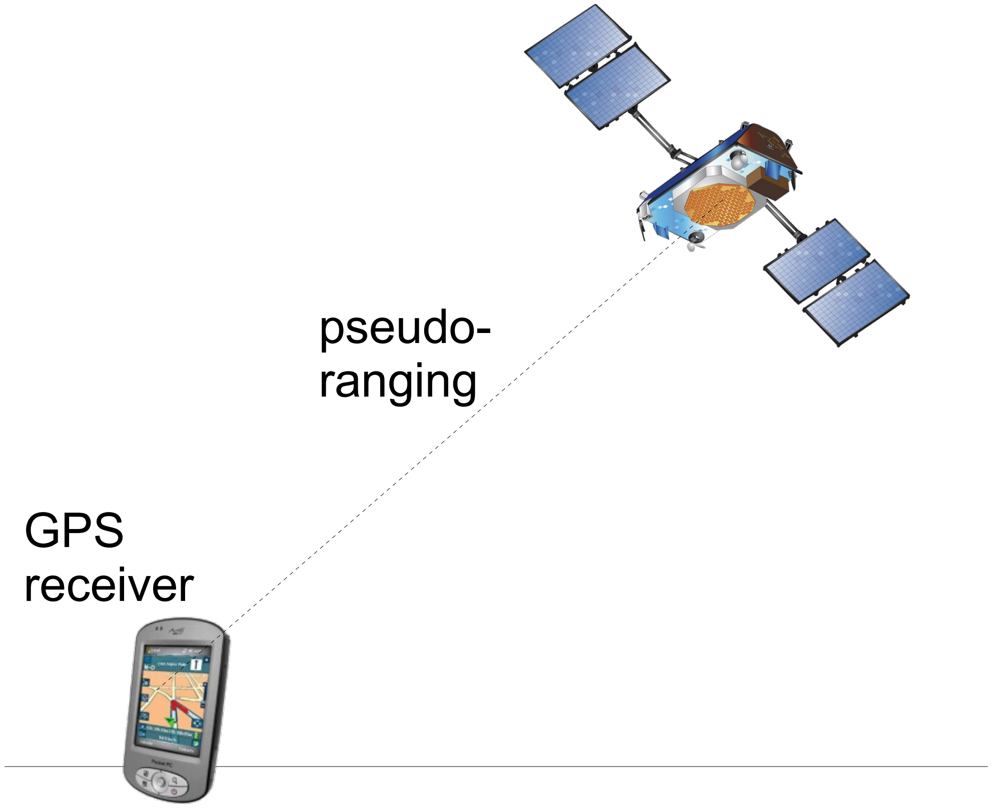


GNSS

- GNSS = Global Navigation Satellite System
- Examples:
  - GPS (USA, global)
  - GLONASS (Russia, global)
  - Galileo (UE, under construction)
  - Compass (China, regional, to be expanded to global)

GNSS

- Satellite constellation
- *Pseudo-ranging* operation from satellite to earth
- The satellite periodically broadcasts a navigation message
- The GPS receiver measures the instant of arrival



GNSS

- The satellites are synchronized each other (atomic clocks)
- The ground GPS receiver and the satellites are *not* synchronized (sky-ground clock difference: $\Delta t_{S\text{-}G}$)
- The GPS receiver knows the satellite position (X_S) and time ($t_S^{(tx)}$) when the satellite broadcasted the message

$$\left|X_S - \underbrace{X_G}_{\text{3 unknowns (x, y, z)}}\right| = \left(t_G^{(rx)} - t_S^{(tx)} - \underbrace{\Delta t_{S\text{-}G}}_{\text{1 unknown}}\right) \cdot c \longleftarrow \text{Pseudo-ranging result}$$

GNSS

- Four pseudo-rangings with four different satellites

$$\begin{cases} \left|X_{S_1} - X_G\right| = \left(t_{G_1}^{(rx)} - t_{S_1}^{(tx)} - \Delta t_{S\text{-}G}\right) \cdot c \\ \left|X_{S_2} - X_G\right| = \left(t_{G_2}^{(rx)} - t_{S_2}^{(tx)} - \Delta t_{S\text{-}G}\right) \cdot c \\ \left|X_{S_3} - X_G\right| = \left(t_{G_3}^{(rx)} - t_{S_3}^{(tx)} - \Delta t_{S\text{-}G}\right) \cdot c \\ \left|X_{S_4} - X_G\right| = \left(t_{G_4}^{(rx)} - t_{S_4}^{(tx)} - \Delta t_{S\text{-}G}\right) \cdot c \end{cases}$$

- The pseudo-rangings are affected by an error
  - They do not intersect in a single point
  - Least-square-error solution is computed

Civil and military GNSS

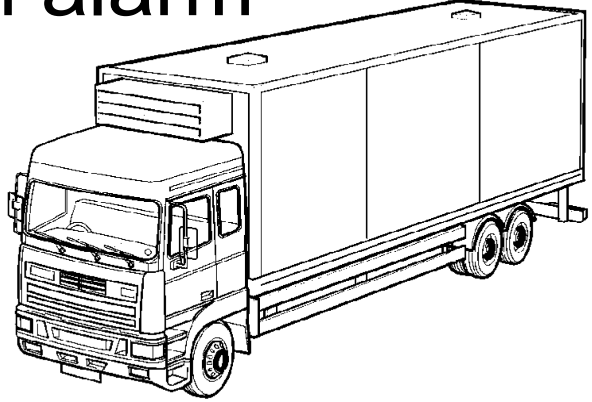
- Most of GNSS system (e.g. GPS) uses two types of navigation signals:
  - Civil navigation signal
  - Military navigation signal
- The military navigation signal uses *spread-spectrum modulation* with a secret spreading code
  - It is hard to *receive*, to *synthesize*, or to *jam* military signals unless the spreading code is known

GPS jamming/spoofing

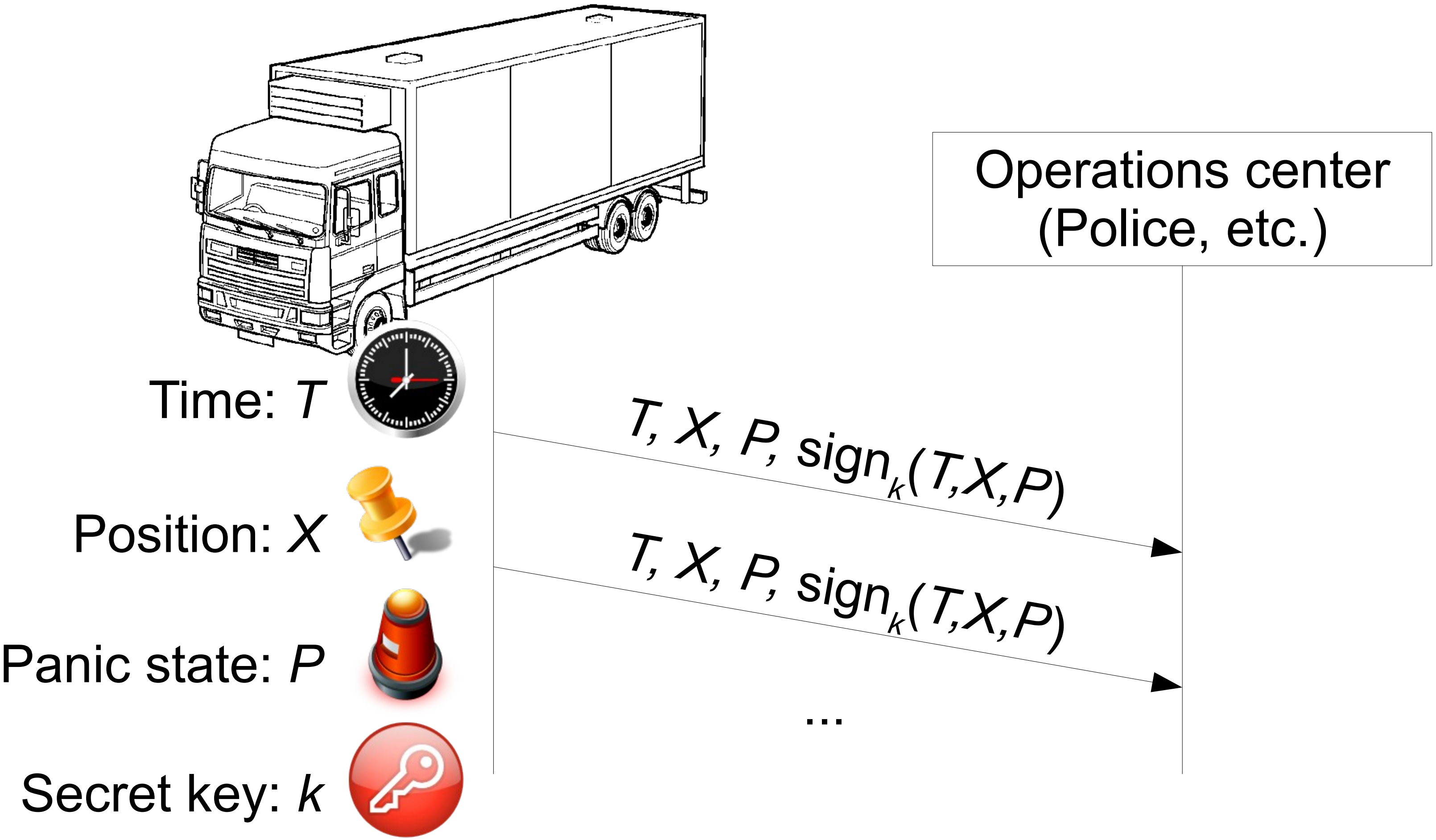
- *GPS jamming*: to disturb the bandwidth on which the (civil) navigation signals are transmitted, in such a way to interrupt the navigation service
- *GPS spoofing*: to synthesize false (civil) navigation signals, in such a way to deceive the navigation service

Truck stealing

- Suppose a truck is carrying valuable goods (gold, etc.)
- The truck is protected by a *satellite anti-theft system*
  - GPS receivers + cellular connection to an operations center (usually by SMSs)
- The driver has also a "*panic button*" with which he can send an alarm



Truck stealing



Time: T

Position: X

Panic state: P

Secret key: k

Operations center
(Police, etc.)

$T, X, P, \mathrm{sign}_k(T,X,P)$

$T, X, P, \mathrm{sign}_k(T,X,P)$

...

Truck stealing

- If the signature is bad, an alarm will be raised
- If no updates are received for more than ten minutes to the police station, an alarm will be raised
- If the panic-state is “pushed”, an alarm will be raised
- If an alarm is raised, a police helicopter team will arrive

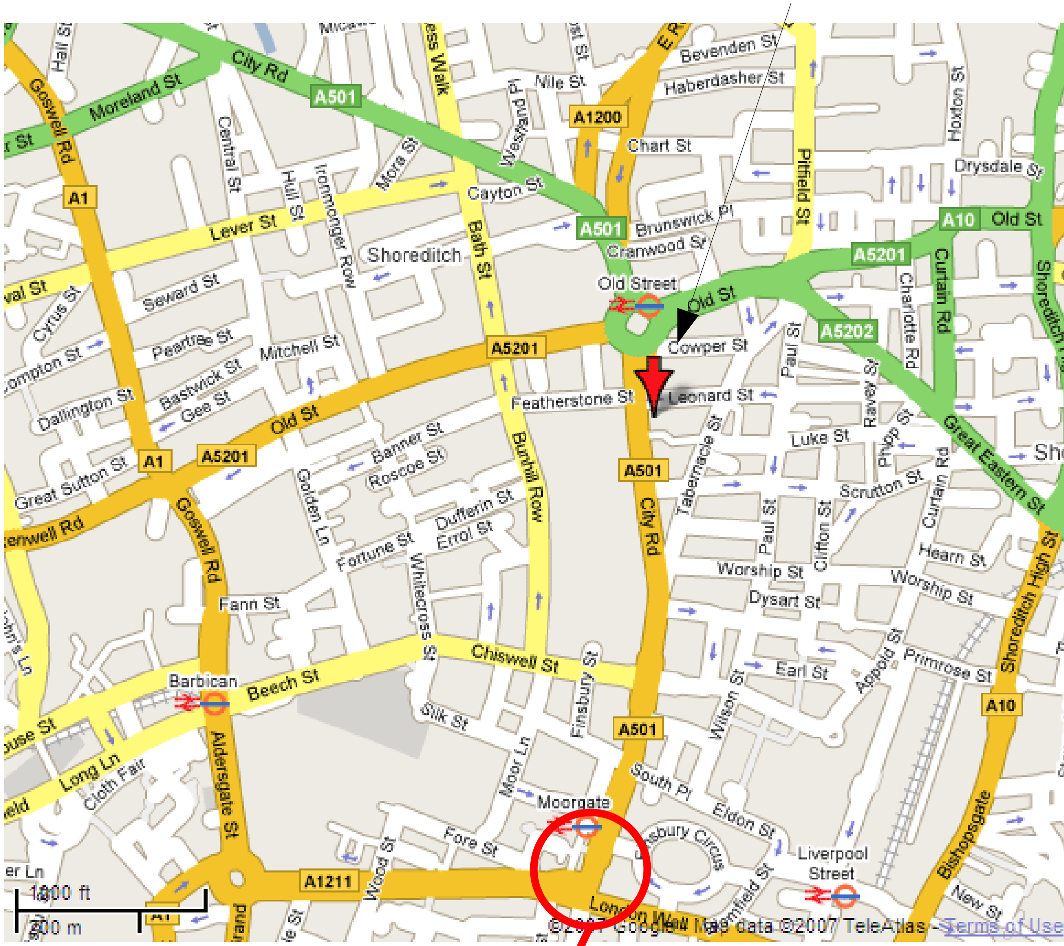
Truck stealing

- Buy (or borrow) a GPS signal simulator
  - For example: Spirent GSS6700 Multi-GNSS Constellation Simulator System

Truck stealing

- Follow the truck and spoof its GPS receiver
- Make the police station believe that the truck has stopped at a service station
- Wait until the truck is far away from its fake position

True position



Fake position

Truck stealing

- *Make the truck stop!*
- If the driver pushes the panic button, the police helicopters will reach the fake position
- Once you have the control of the truck, disable all the other security mechanisms

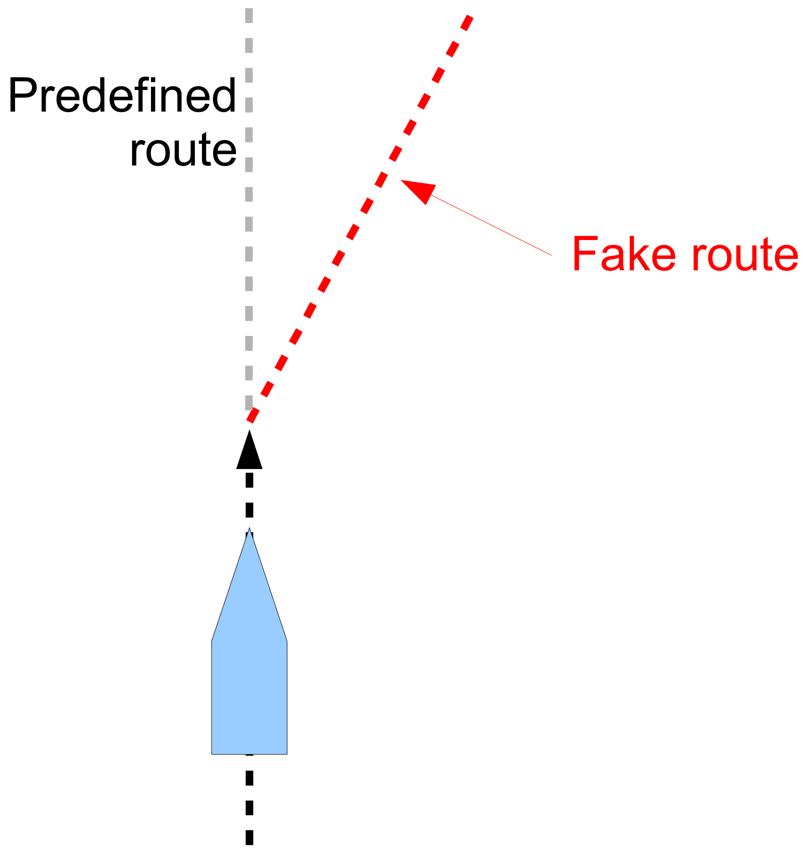
Attack performed in Russia, 1999

Boat hijacking

- A boat follows automatically a predefined route
- The route-following is controlled by means of GPS

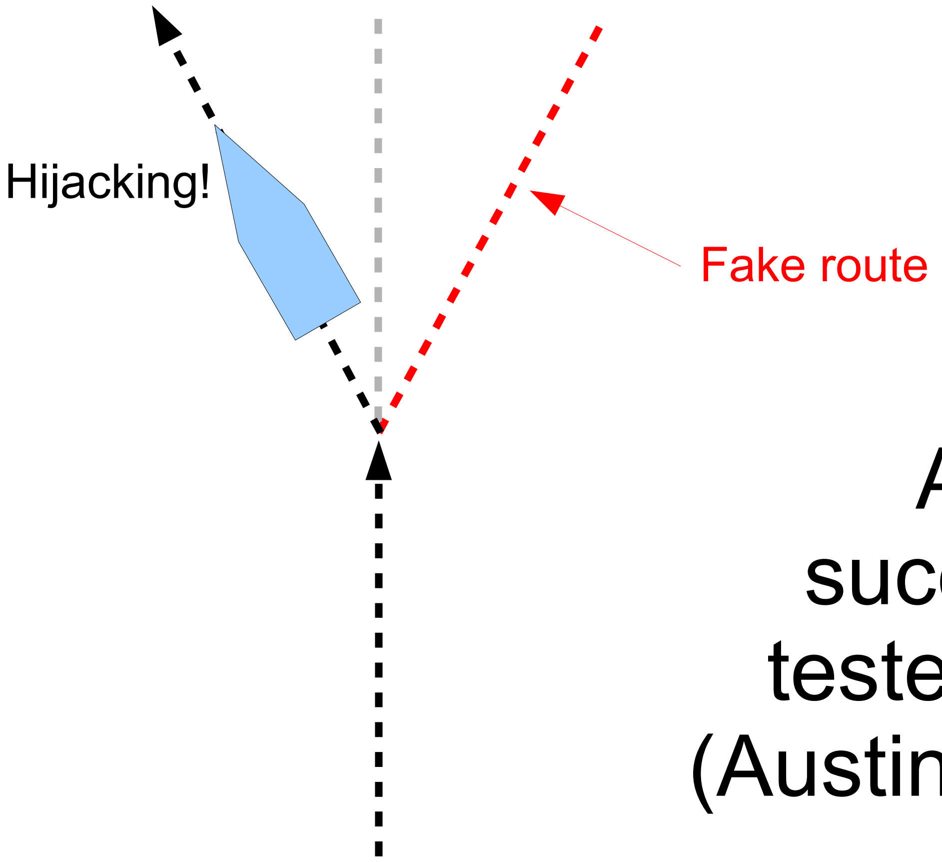
Boat hijacking

- Follow the boat and spoof its GPS receiver
- Make it believe that it *deviated* from the route



Boat hijacking

- The control system tries to *correct* the route to the predefined one
- The boat turns left



Attack successfully tested in 2012 (Austin University)

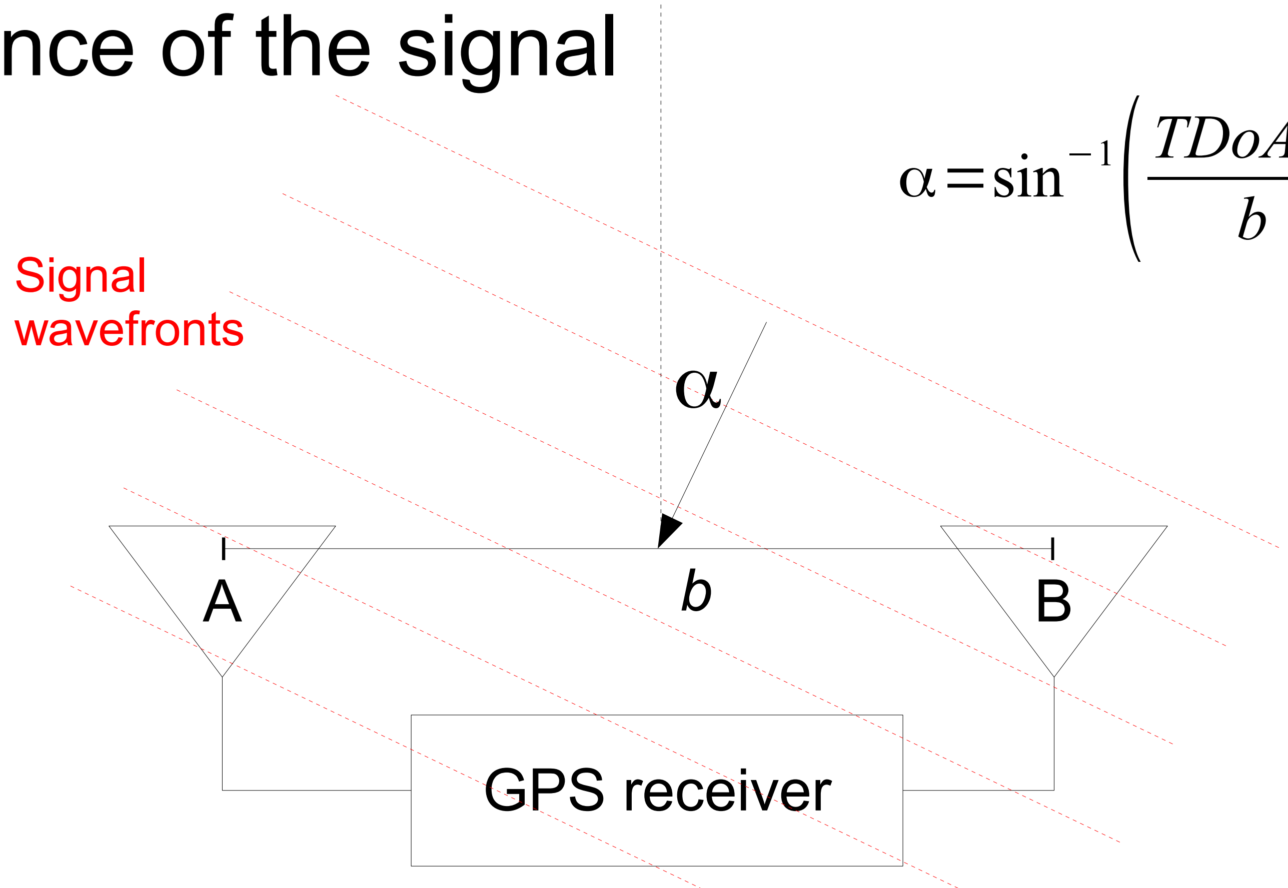
Secure GPS

- Main problems of securing existing (civil) GPS:
  - One-way communication (no distance bounding!)
  - Legacy protocols (GPS messages are not authenticated)
  - Protocol modifications require long deployment times (tens of years)
    - European Galileo will be (probably) authenticated
  - Navigation signals reach earth with *very low power*
    - It is easy to overshadow them with fake signals

Multi-antenna defense

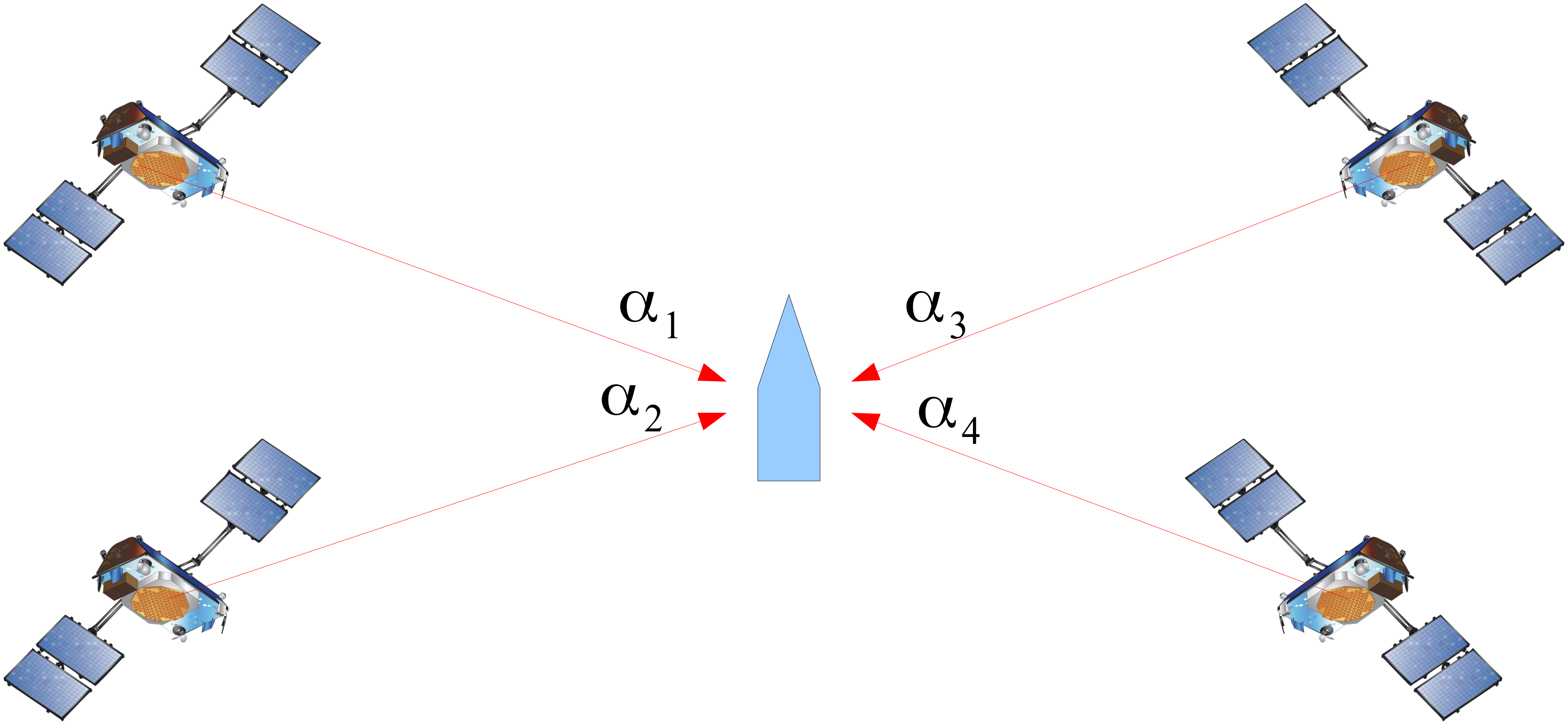
- *Idea*: equip the GPS receiver with two antennas
- By measuring the *time difference of arrival* (*TDoA*) it is possible to determine the angle of incidence of the signal

$$\alpha = \sin^{-1}\left(\frac{TDoA \cdot c}{b}\right)$$



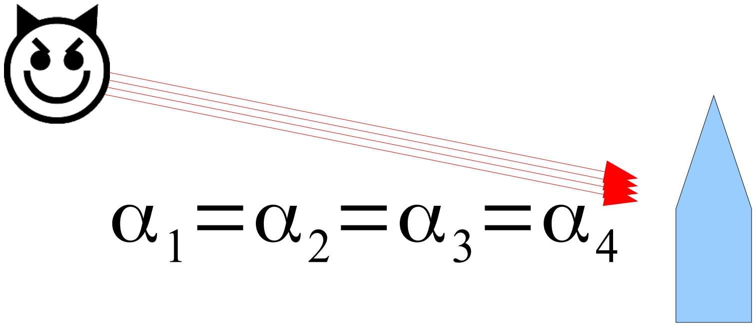
Multi-antenna defense

- In the honest case, the received signals have different angles of incidence (one for each satellite)



Multi-antenna defense

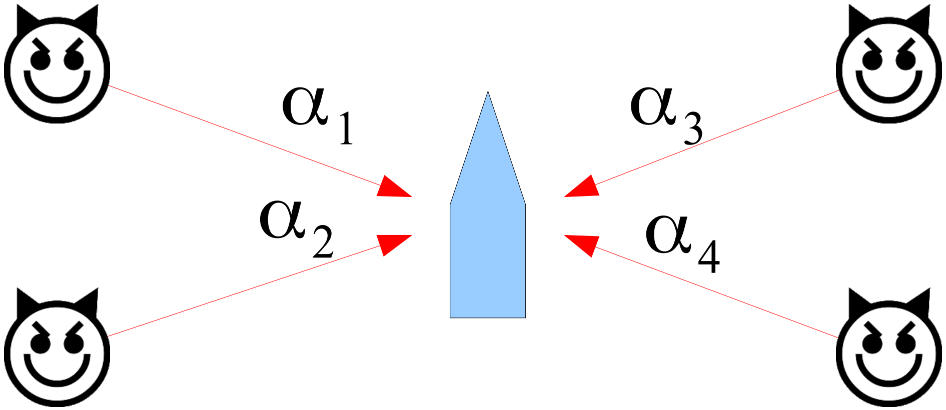
- In the adversarial case, the received signals has the same angle of incidence
- If the the angles of incidence are equal, then *reject the position measurement*



$$\alpha_1=\alpha_2=\alpha_3=\alpha_4$$

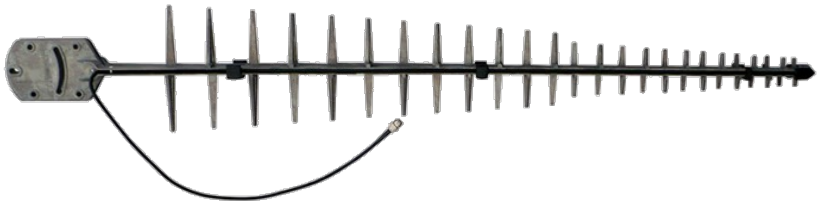
Security analysis

- Colluding adversaries could simulate the angles of incidence of several satellites

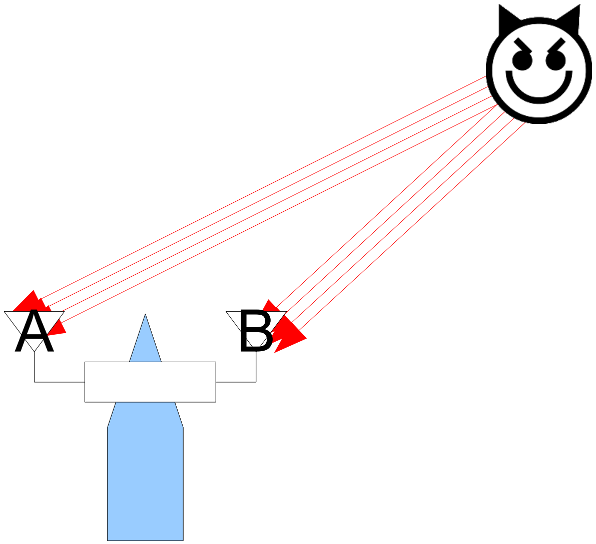


Security analysis

- A single adversary equipped with two directional antennas can hit the two receivers with different signals

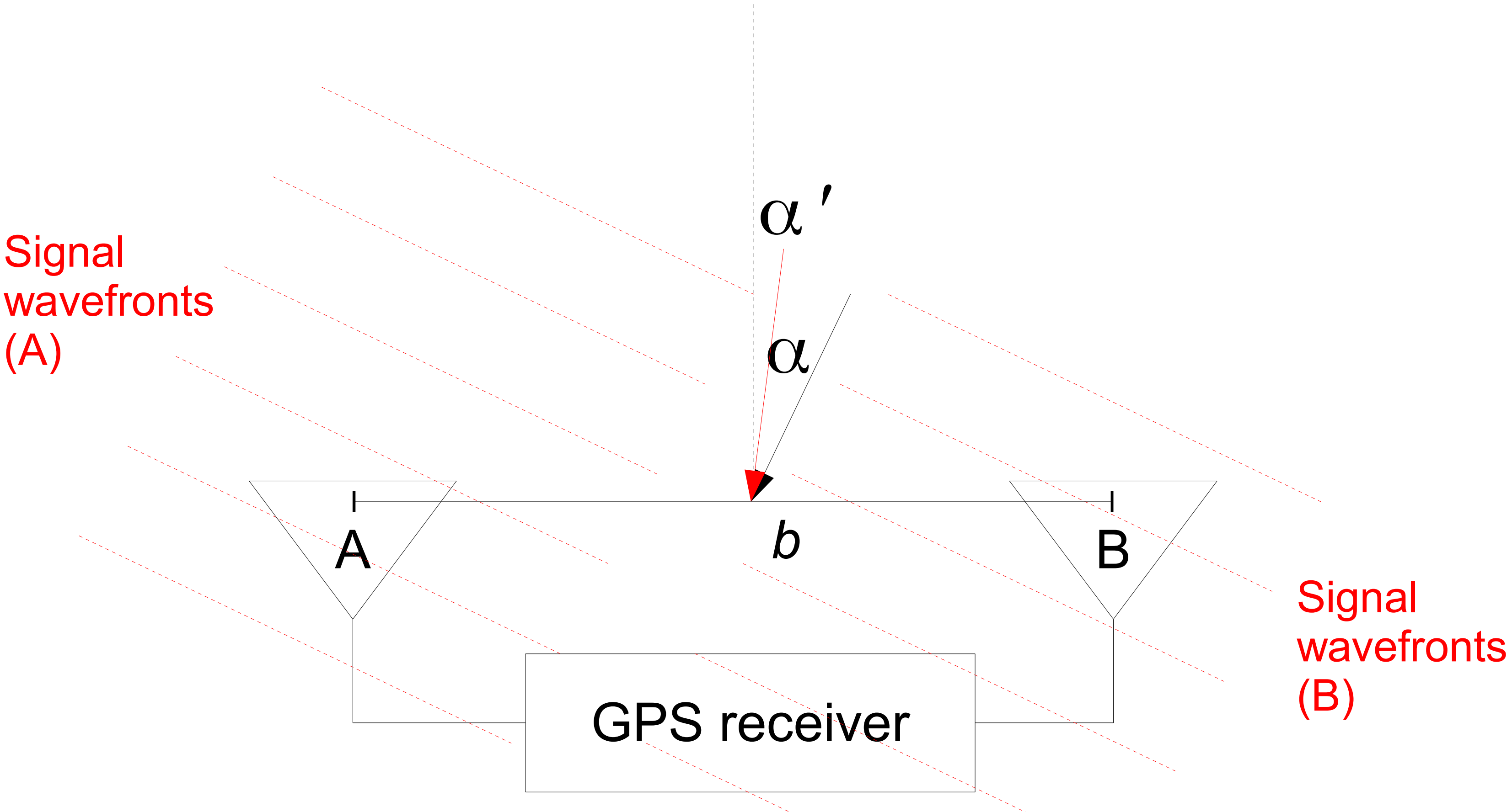


Directional antenna



Security analysis

- In this way, the adversary can spoof the angle of incidence (α') of each simulated satellite



Security analysis

- The multi-antenna defense is cheap, but protects only against a single point-transmitter adversary
- More sophisticated attacks are successful
  - multiple point-transmitters
  - directional-transmitter

References

- Srdjan Čapkun and Jean-Pierre Hubaux. *"Secure positioning in wireless networks."* IEEE Journal on Selected Areas in Communications. 2006.
  - Only Sections I, II, IV
- Paul Y. Montgomery, Todd E. Humphreys, and Brent M. Ledvina. *"A multi-antenna defense: Receiver-autonomous GPS spoofing detection."* Inside GNSS 4.2 (2009): 40-46.
- ***(Optional***: Jerry T. Chiang, Jason J. Haas, Jihyuk Choi, Yih-Chun Hu, *“Secure Location Verification Using Simultaneous Multilateration.”* IEEE Transactions on Wireless Communications. 2012.***)***
  - Only Sections I, III, IV