Illusion and Dazzle: Adversarial Optical Channel Exploits against Lidars for Automotive Applications

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CHES'17

System Security Lab @ Korea Advanced Institute of Science and Technology

Presenter: Sanggu Han

Most slides are borrowed from author's slide

Transition toward Autonomous Cars

Alphabet's self-driving car company Waymo announces $2.5 billion investment round

PUBLISHED WED, JUN 16 2021•8:30 AM EDT | UPDATED WED, JUN 16 2021•10:11 AM EDT

Autonomous vehicle delivery firm Nuro adds $600MM investment

November 2, 2021 - General News

Autonomous driving startup Momenta raises another $500M

Self-driving truck startup Kodiak Robotics raises $125M

Kirsten Korosec @kirstenkorosec / 1(

Oxbotica raises $13.8M from Ocado to build autonomous vehicle tech for the online grocer's logistics network

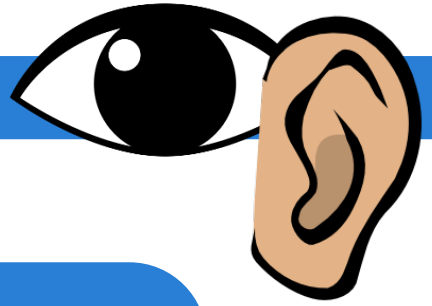
Ingrid Lunden @ingridlunden / 3:37 PM GMT+9 • April 16, 2021

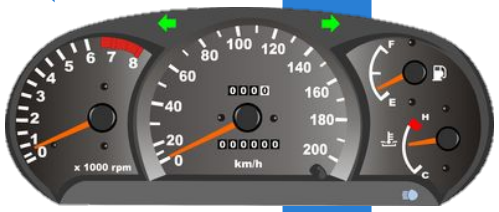
Comment

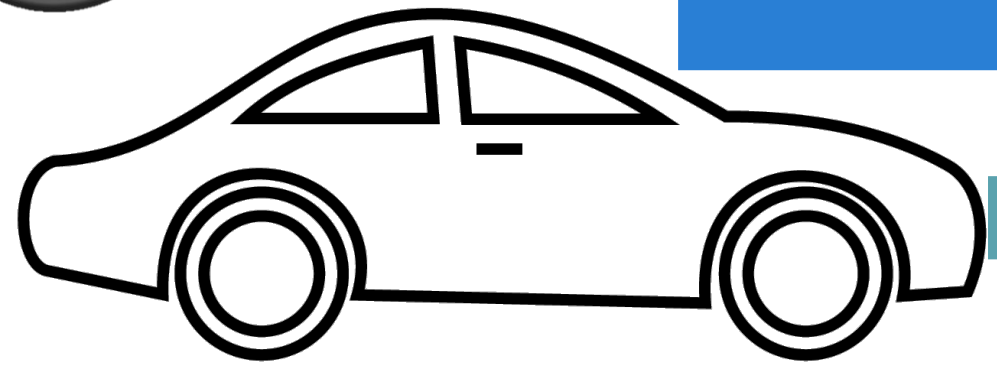
NISSAN NVIDIA Audi WAYMO HYUNDAI TESLA TOYOTA

and many others....

Human Driving







Manual Driving

Surroundings

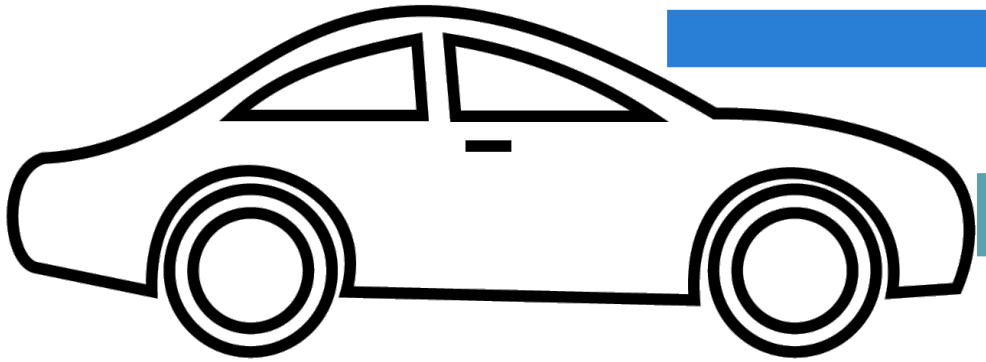
Autonomous Driving: a Sensing & Actuation System

Inter-vehicle Network

GNSS

Intra-vehicle Network

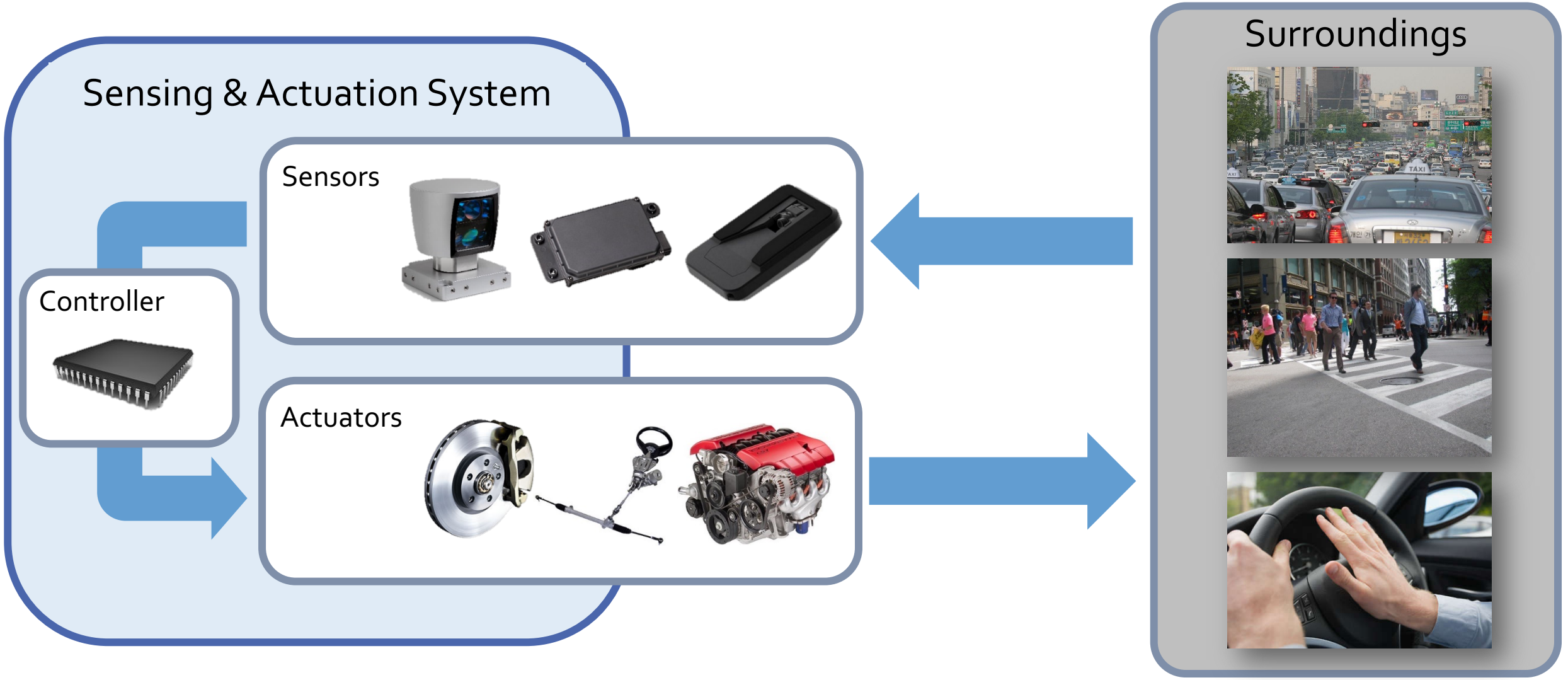
Intra-vehicle Network



Autonomous Driving

Surroundings

Sensor Attacks against Sensing & Actuation Systems



Sensor Attacks against Sensing & Actuation Systems

W/O Security Features

ation System

Sensors



Cont er

Actuators



Surroundings



Introduction

- LiDAR: Light Detection and Ranging

- How attack can launch
  - Saturation attack / Spoofing by relaying attack

- Countermeasures and its limitations

Lidar

- **Li**ght **D**etection **a**nd **R**anging
  - cf) **Ra**dio **D**etection **a**nd **R**anging → radar

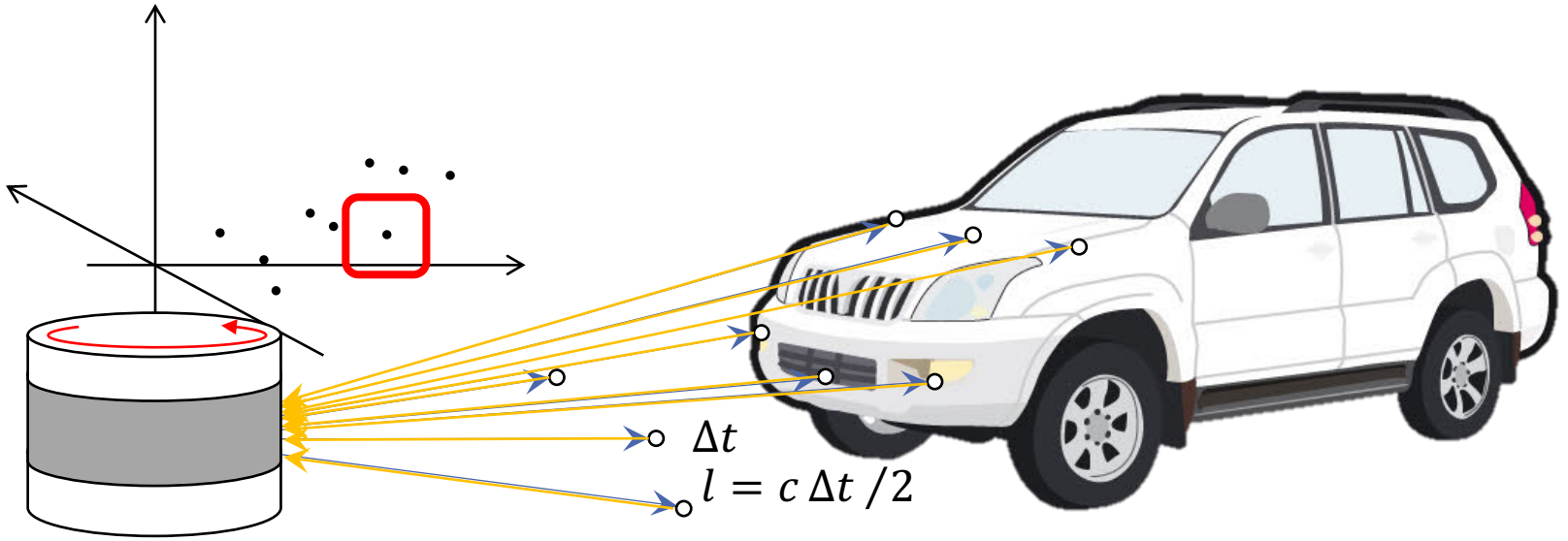
Lidar

- **Li**ght **D**etection **a**nd **R**anging
  - cf) **Ra**dio **D**etection **a**nd **R**anging → radar

- Lots of strengths
  - Source of highest spatial resolution
    - Much better than radars / ultrasonic sensors
    - ∵ Superior directivity of laser beam
  - Highly autonomous platforms tend to have lidars

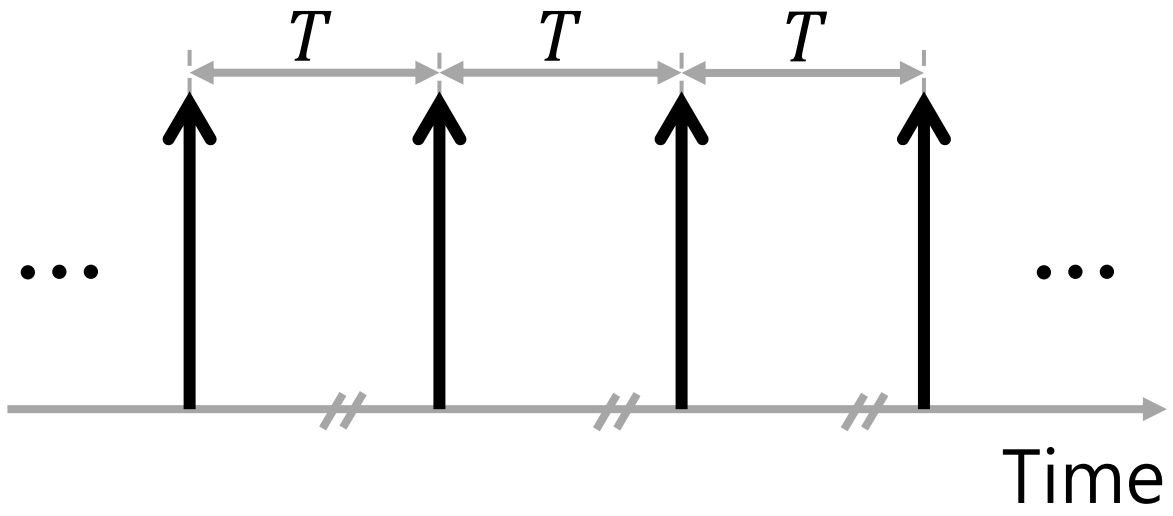
Lidar

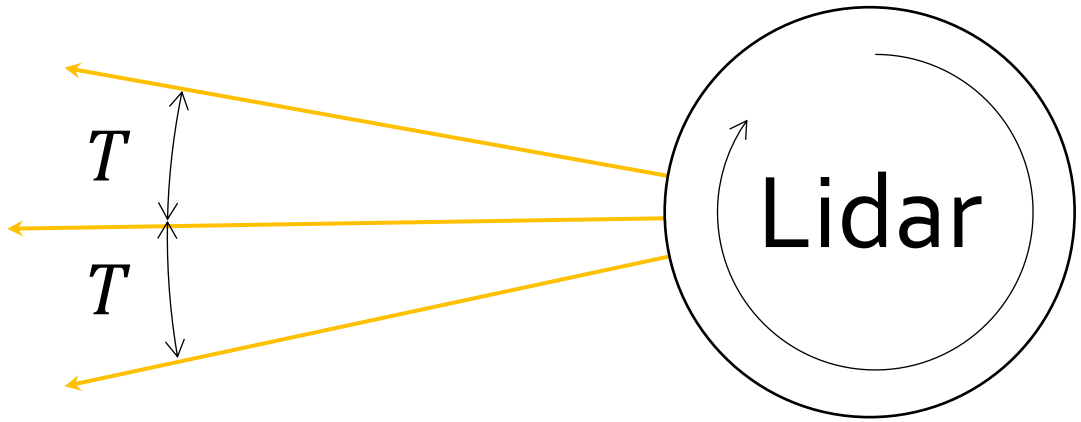
- Working principle
  - Similar to radars / sonars / ultrasonic sensors except media
  - Multi-layer scanning lidar ≙ rotating 3D-mapping lidar



Lidar

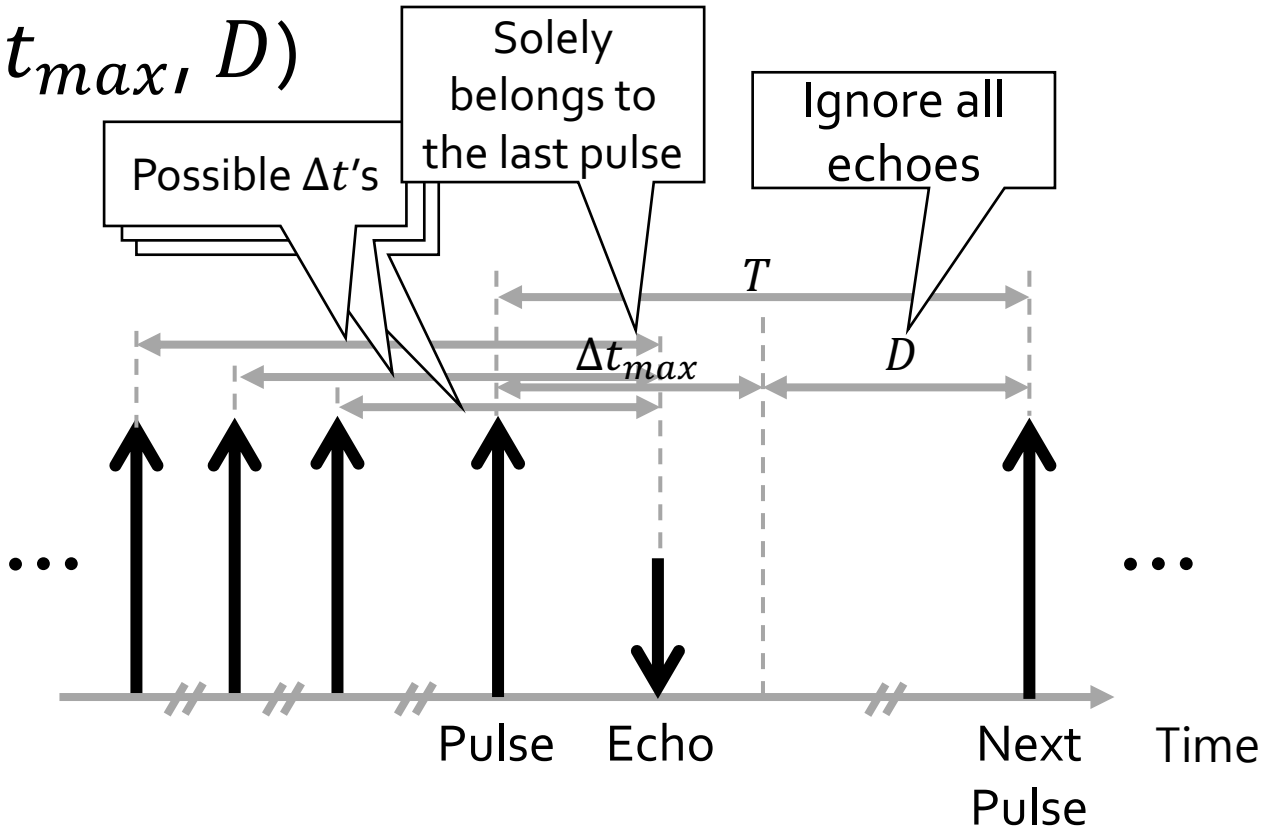
- Important parameters
  - Pulse repetition time (PRT, T)





Lidar

- Important parameters
  - Pulse repetition time (PRT, T)
  - Receiving time / dead time (Δt_{max}, D)
    - To limit the ambiguity
    - Lidar range l_{max} → $c\Delta t_{max}/2$



Lidar

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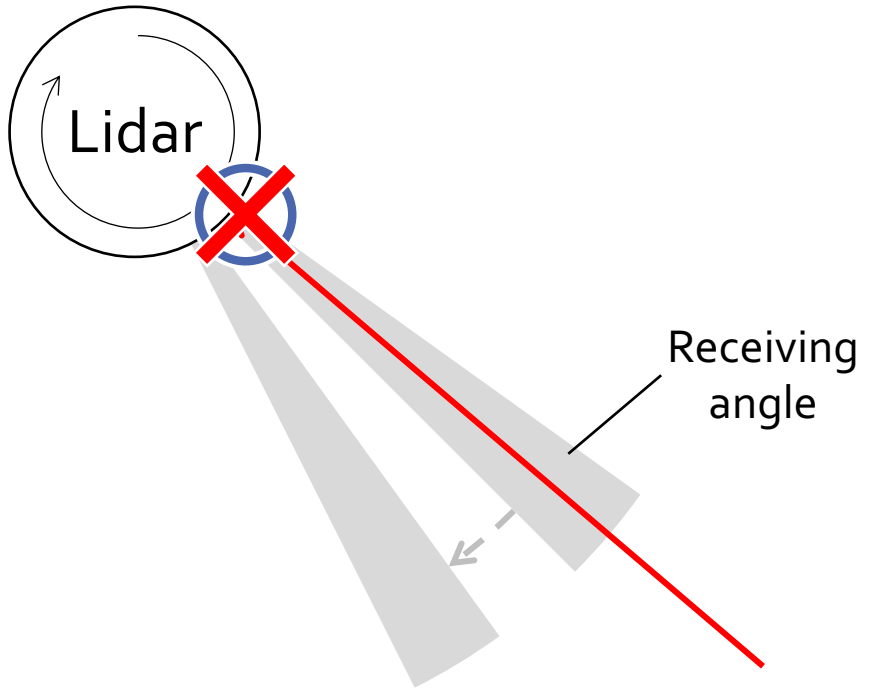
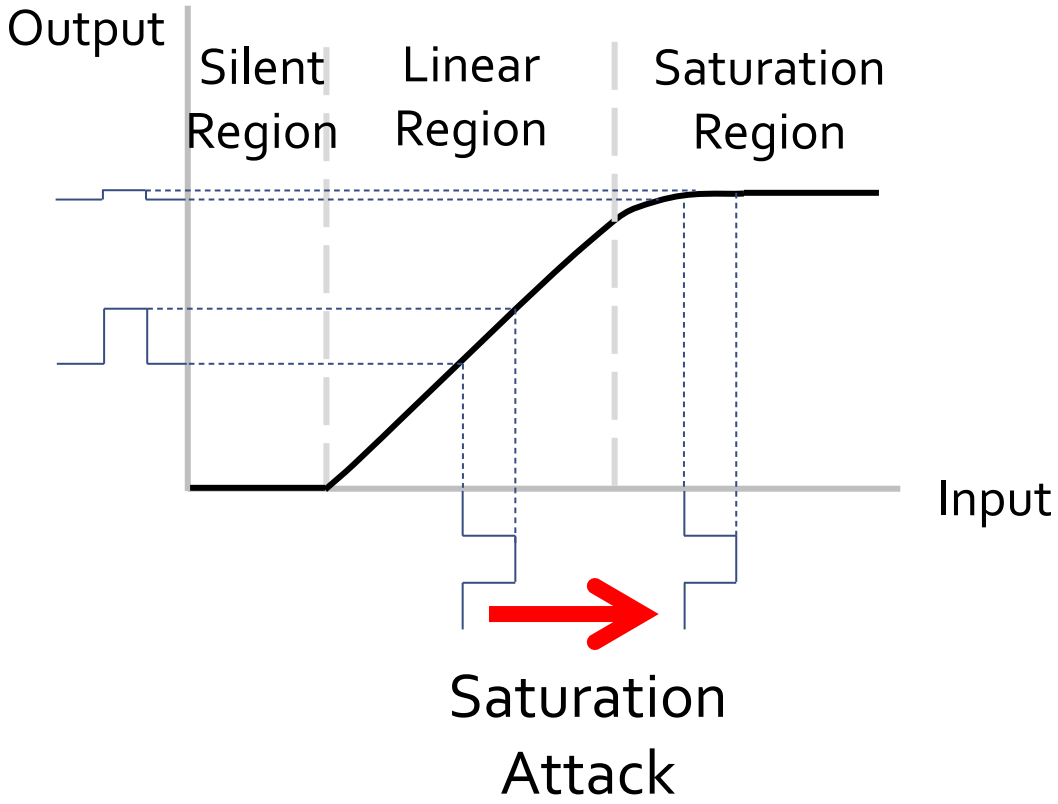
  - Receiving time / dead time (Δt_{max}, D)
    - To limit the ambiguity
    - Lidar range $l_{max} \rightarrow c\Delta t_{max}/2$
  - Receiving angle
    - Angle of receiver aperture
    - If precisely calibrated,
      covering up to the farthest point is enough



Sensor Attacks

Sensor Saturating

- Exploiting the transition curve



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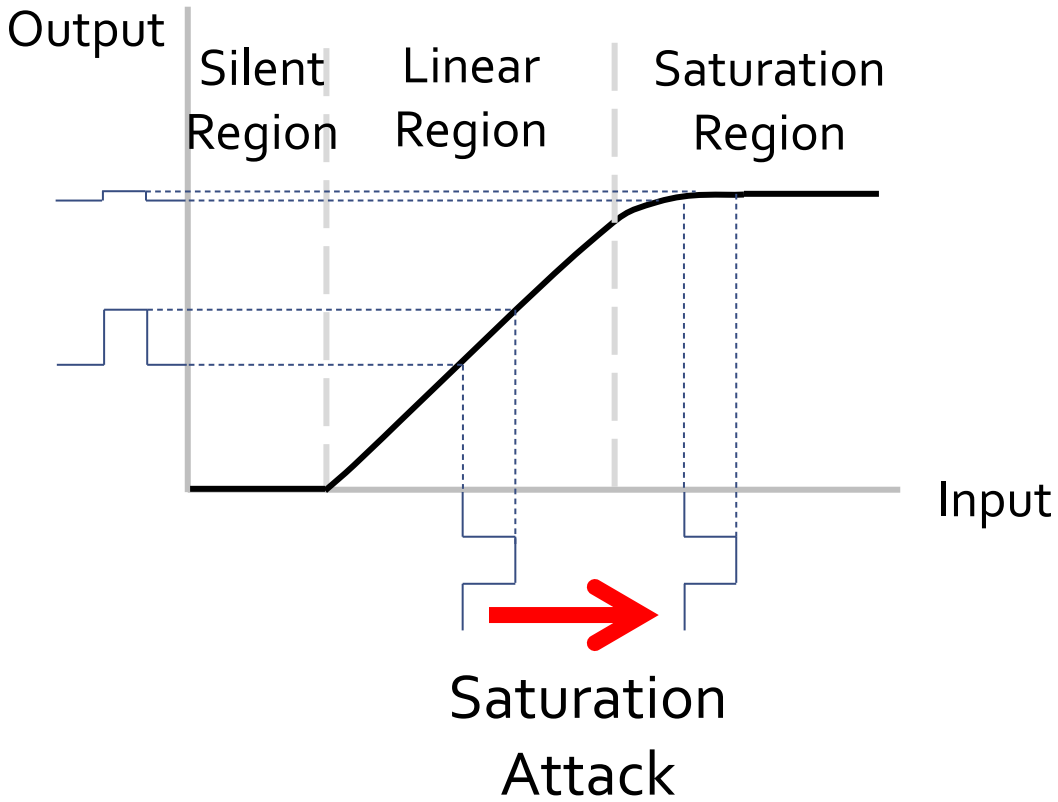
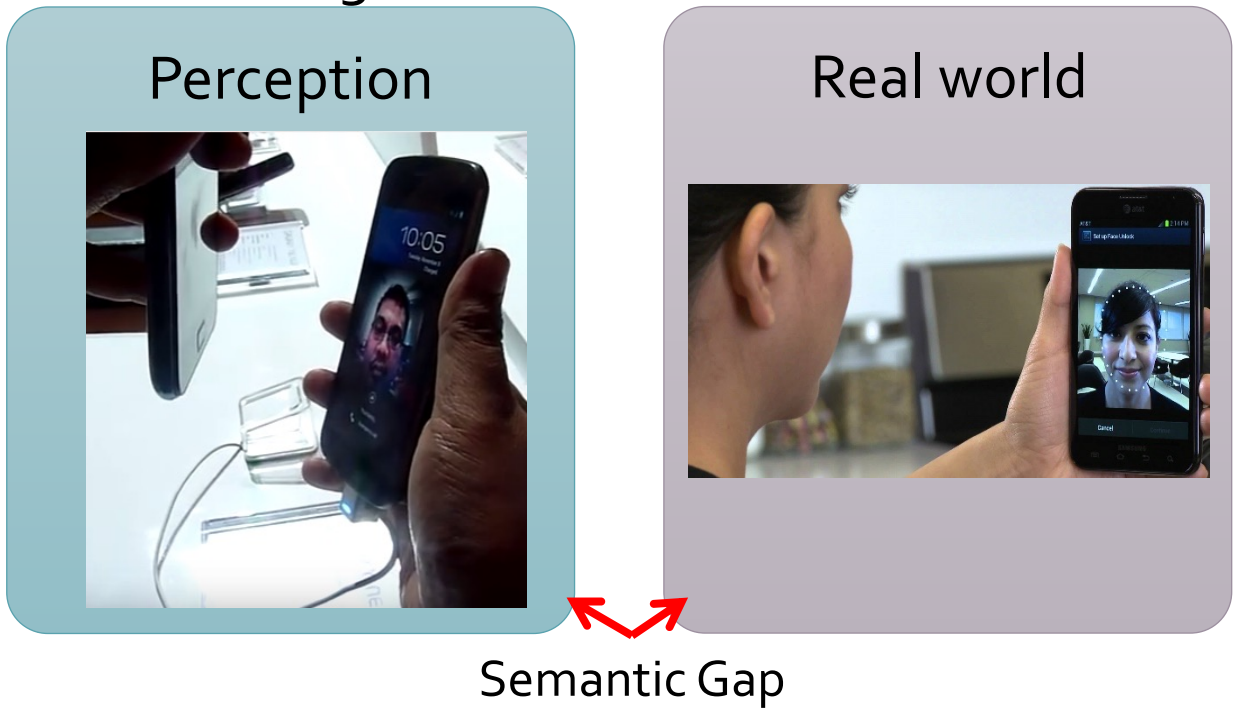


Sensor Spoofing

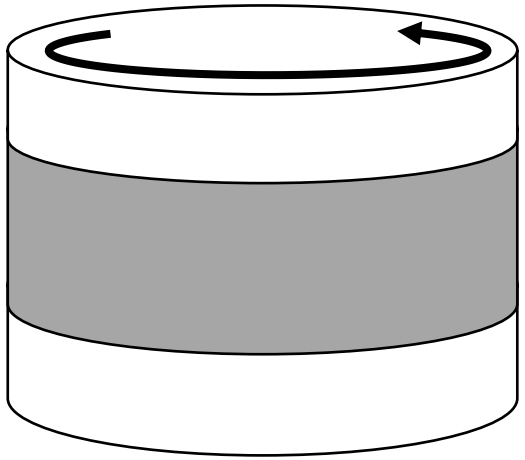
◆Deceiving sensors



- Lidar spoofing: make a lidar see an object that does not exist in fact

Target System

A scanning lidar system

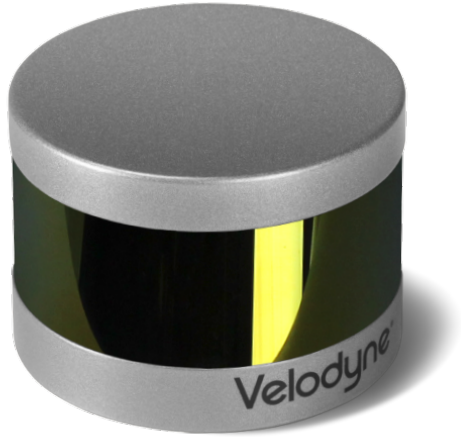


Exposed to the exterior

Target System

- Velodyne's VLP-16
  - Outputs via Ethernet in UDP packets ➔ Used VeloView to visualize sensing outputs

Price	US$7,999
Laser wavelength	903nm
# of vertical layers	16
Update rate	5/10/20Hz (configurable)
Range	100m
Field Of View	360° (hor.), -15°~15° (ver.)
Angular Resolution	0.1/0.2/0.4°(hor., depends on update rate), 2° (ver.)



Attack Model

- Saturating
  - Can inject light → includes aim & focus capability
  - Attacking light with the same wavelength as the target
  - Attacking light strong enough to saturate

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- Spoofing
  - Injection capability
  - Can receive pinging pulses from the target lidar
  - For inducing closer objects
    - Consistent / predictable ping waveform and PRT
    - Virtually, all COTS automotive lidars meet this

Saturation Attack

- Illuminating the target lidar with intense light source
  - Saturation → unable to sense incoming echoes → blinding
  - Strong attack because saturation itself is inavoidable
  - Detection is easy, but no COTS lidar has this function

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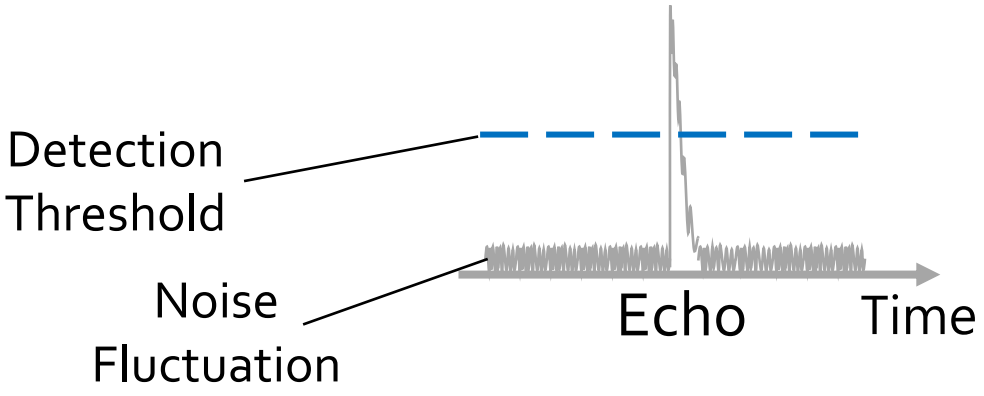
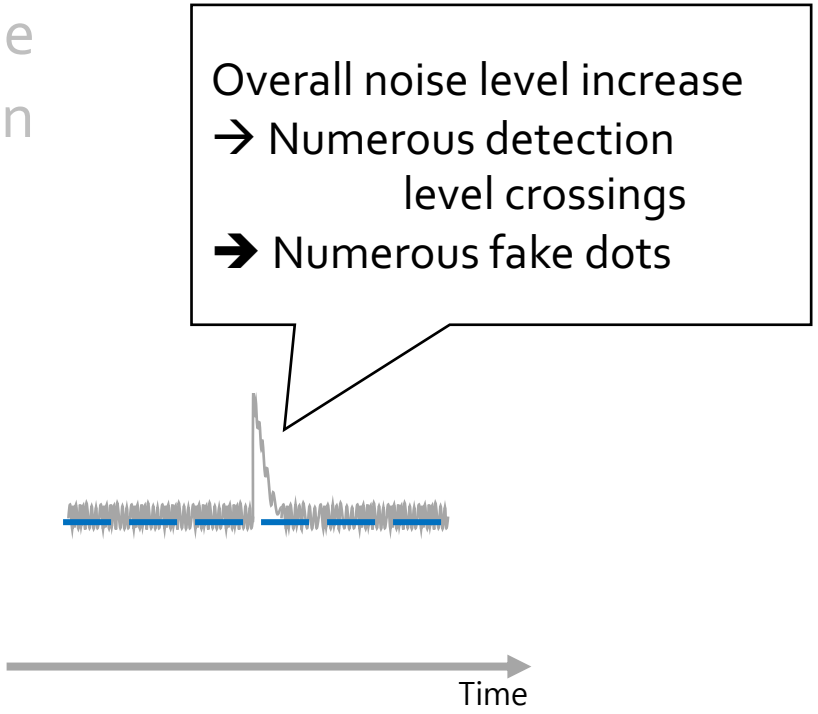


Exposure to weak light source




Lidar Exposure to
Weak Light Source

Saturation Attack

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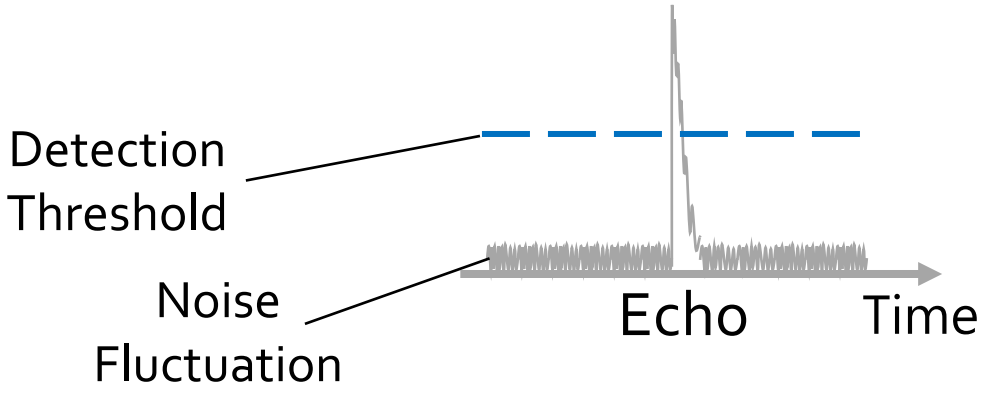
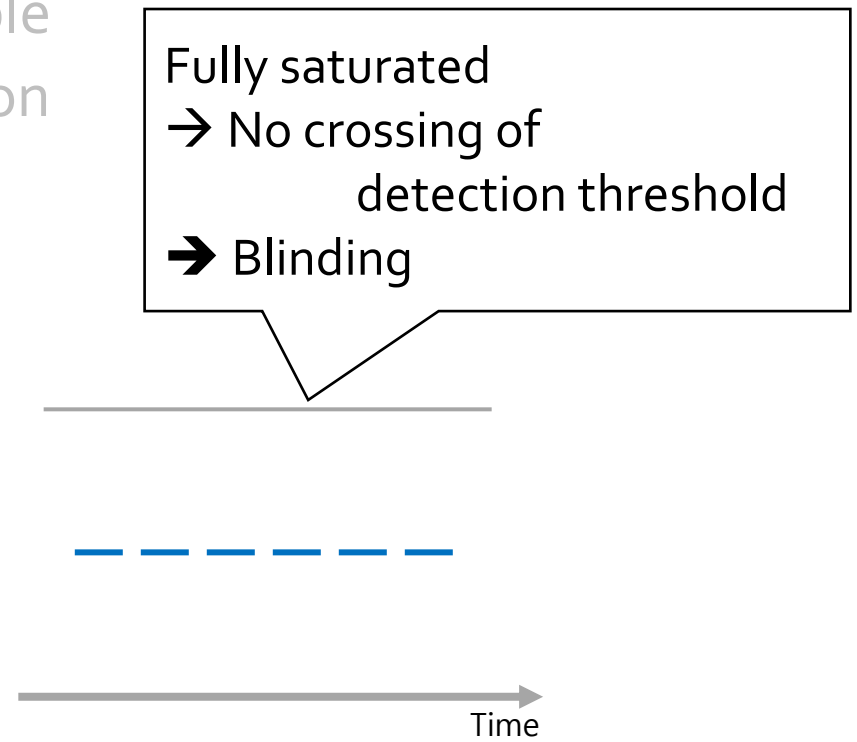
  - Detection is easy, but no COTS lidar has this function
- Effect and cause speculation
  - Weak light injection → numerous fake dots
  - Strong light injection → blinding of a section



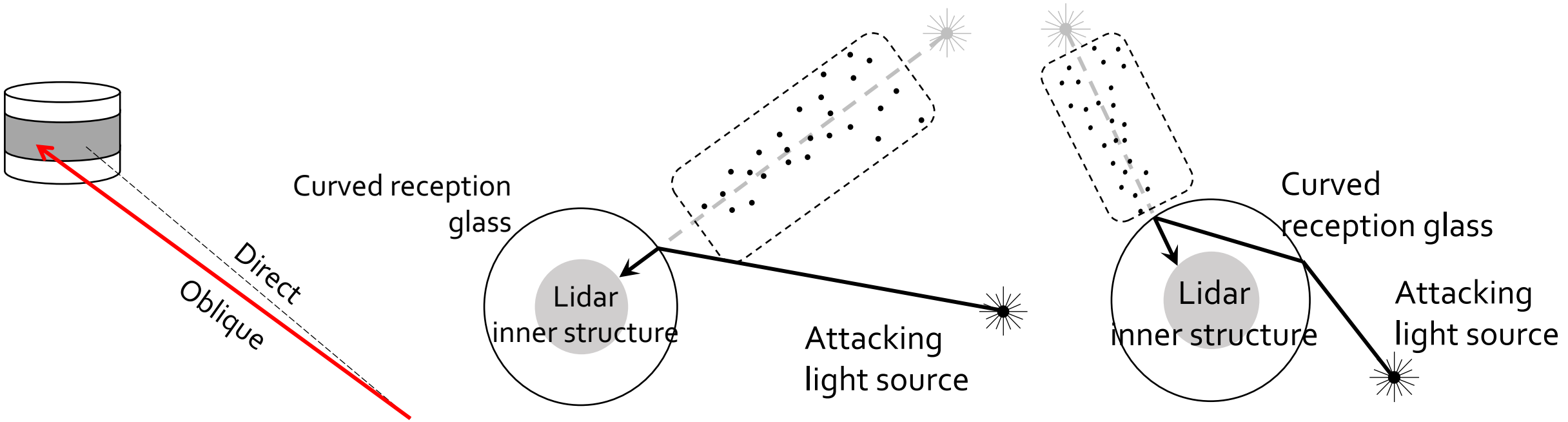
Exposure to Strong light source




Lidar Exposure to
Strong Light Source

Saturation Attack

- Adverse effect of curved reception glass
  - Obliquely illuminating VLP-16
    ➔ fake dots not in the direction of the attacking light



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  - Other lidars also have curved glass (e.g. HDL-32E, LUX mini, M8)

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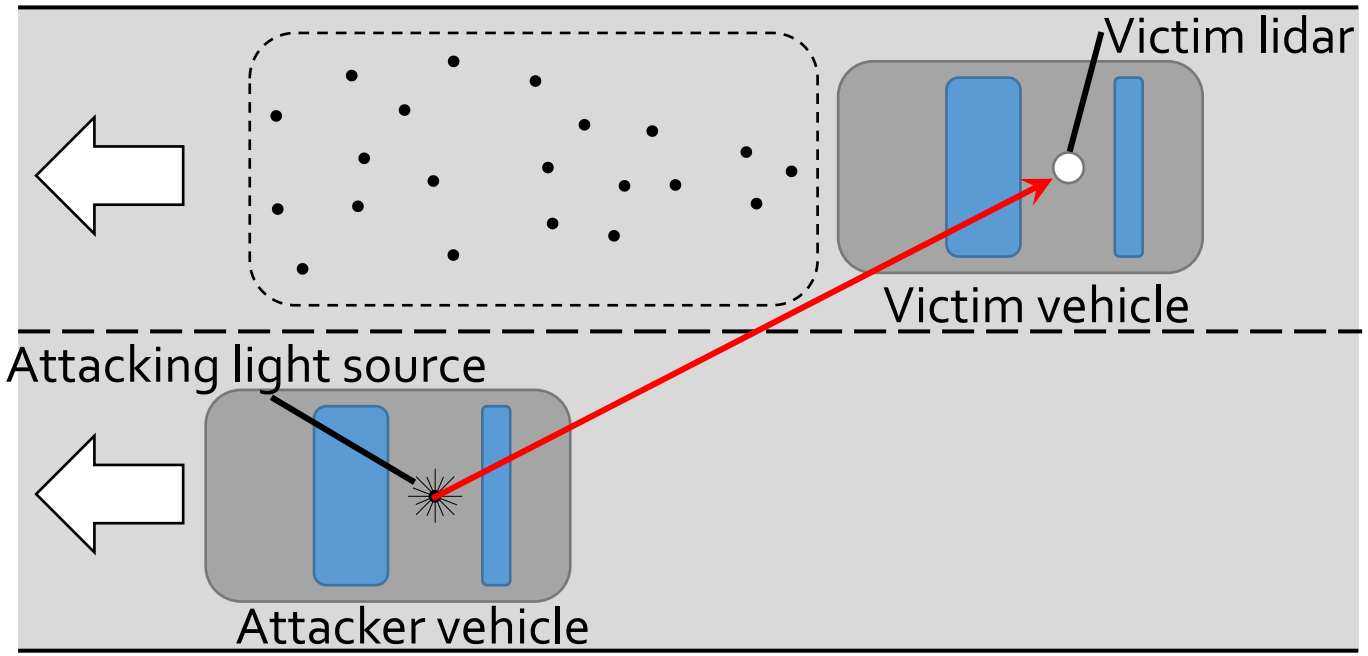


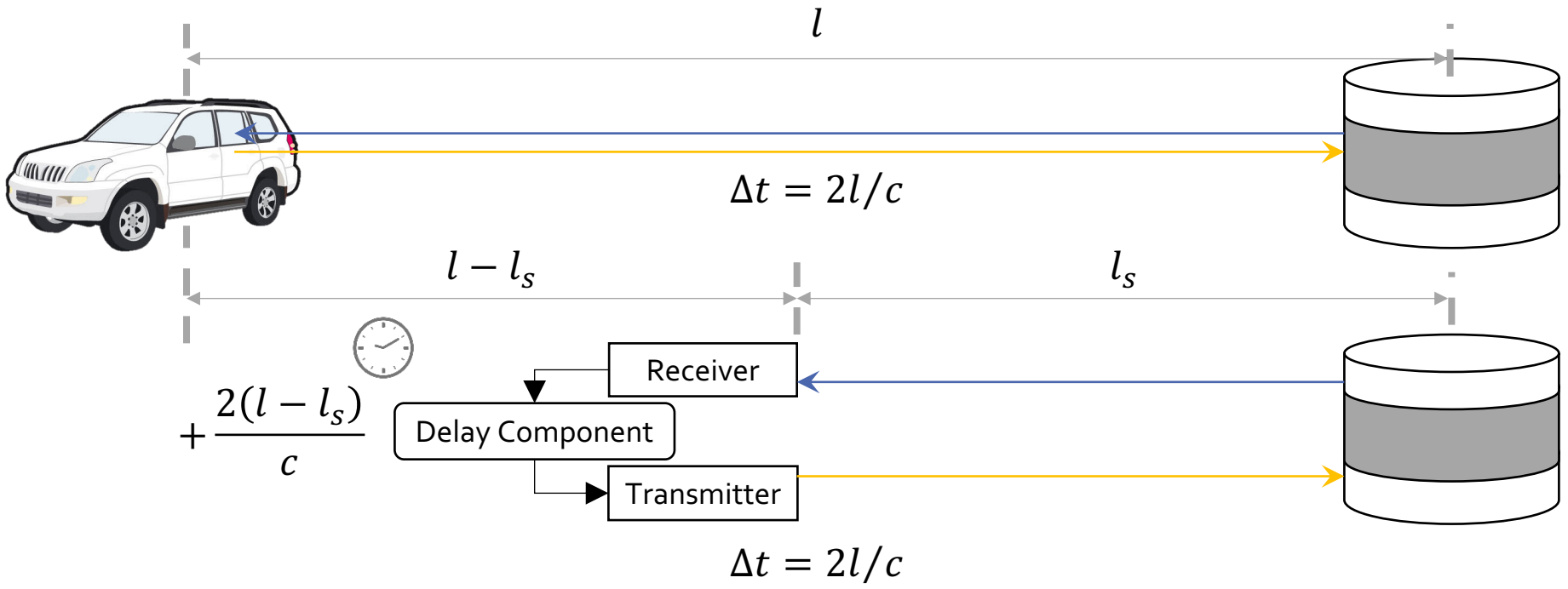
Lidar Obliquely Exposed to Strong Light Source

Saturation Attack

- Stealthy against human since IR laser is invisible,
- For relatively weak light source,
  - They can induce numerous fake dots
- For relatively strong light source,
  - They can make LiDAR completely blind
- By the design of lidar (curved reception glass),
  - They can induce fake dots in direction other than source

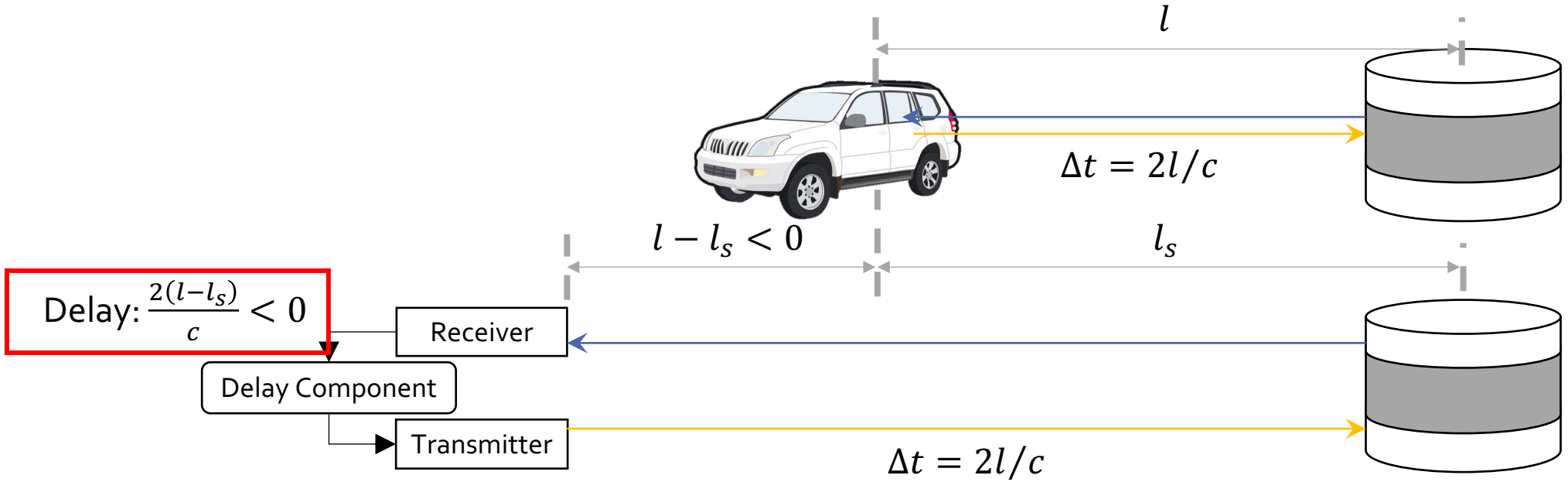
Spoofing by Relaying Attack - Ideal Attack Process

- Inducing a farther fake dot
  - Spoofed fake dots are less important than the spoofer itself



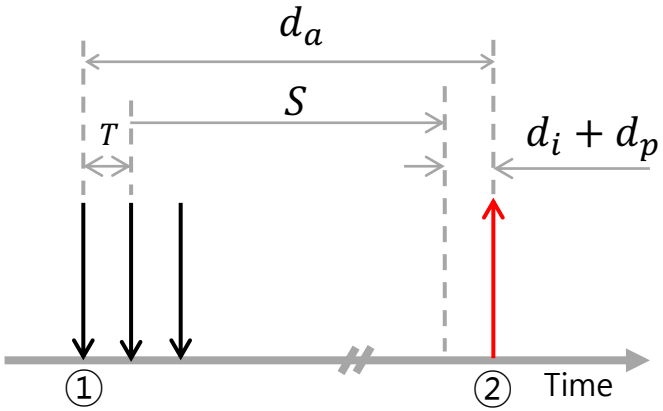
Spoofing by Relaying Attack - Ideal Attack Process

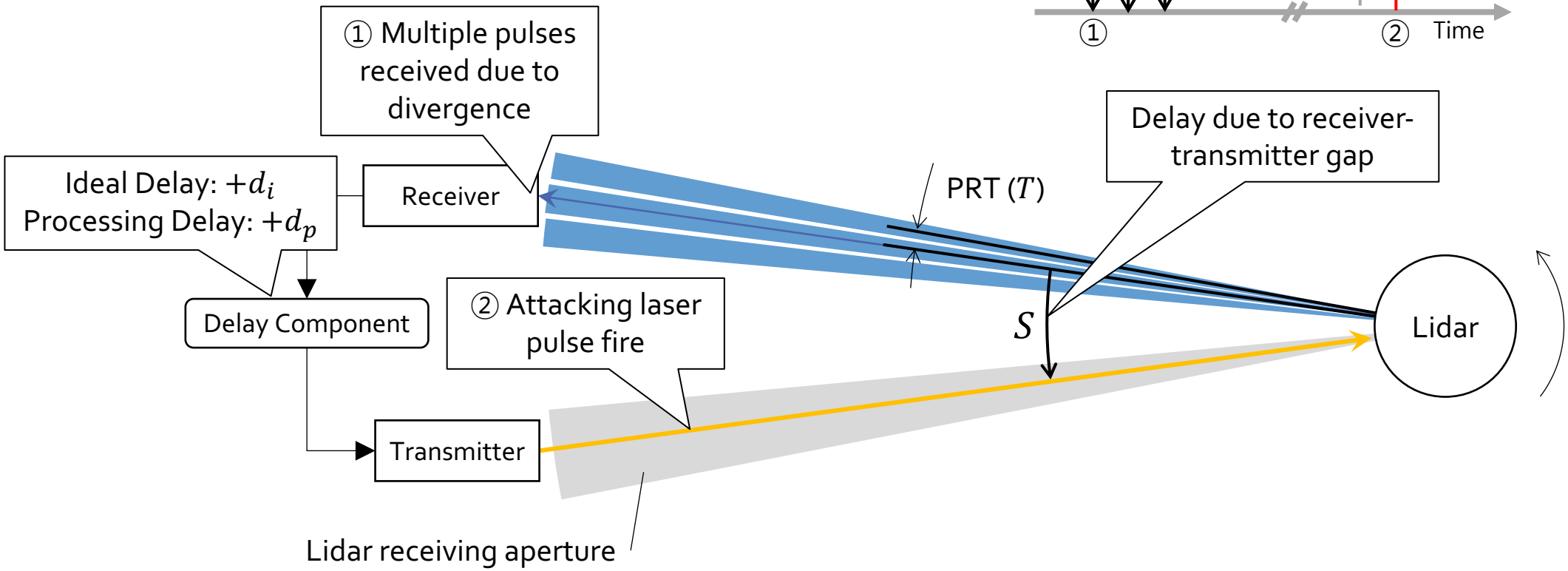
- Why we cannot induce closer fake dots with this model
  - Negative delay required → impossible



Spoofing by Relaying Attack - Actual Attack Process

- Difference from the ideal case
  - Laser beam diverges
  - Receiver-transmitter gap





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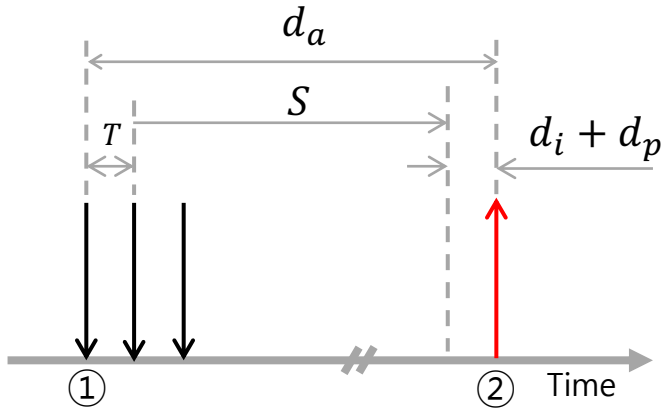
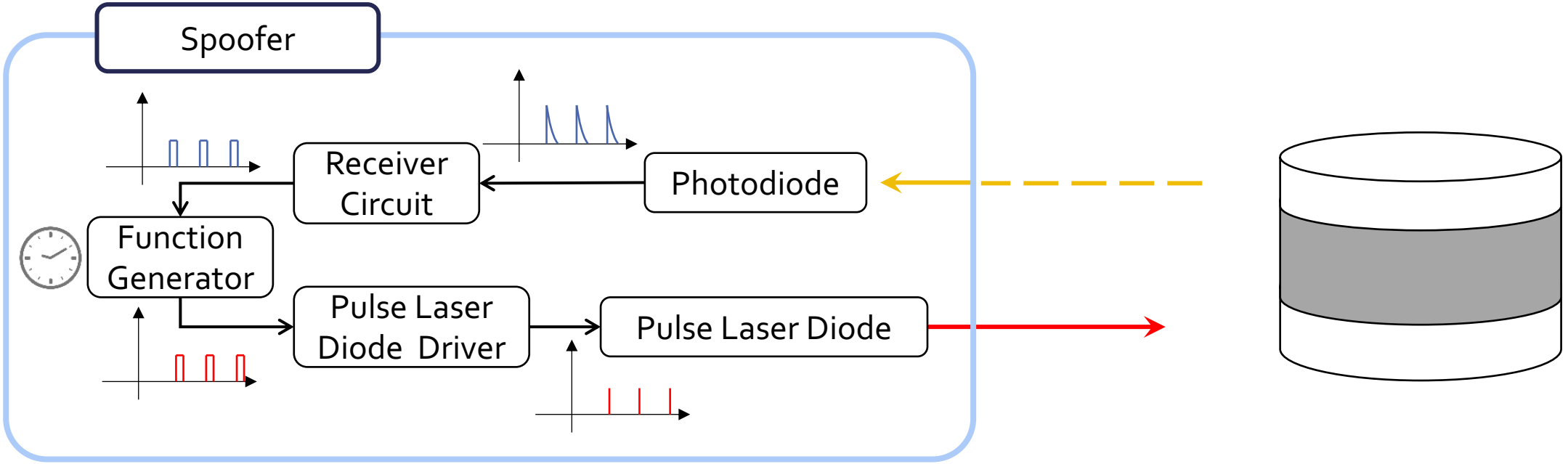


- Why this makes closer fake dots possible
  - $d_a(total\ delay) = d_i + nT + S + d_p$
  - Even if $d_i(ideal\ delay) < 0$ for closer fake dots, $d_a > 0$ ($\because T, S \gg |d_i|$)

Spoofing by Relaying Attack - Experimental Setup

◆Lidar → PD → Receiver Circuit → Function Generator → PLD driver → PLD



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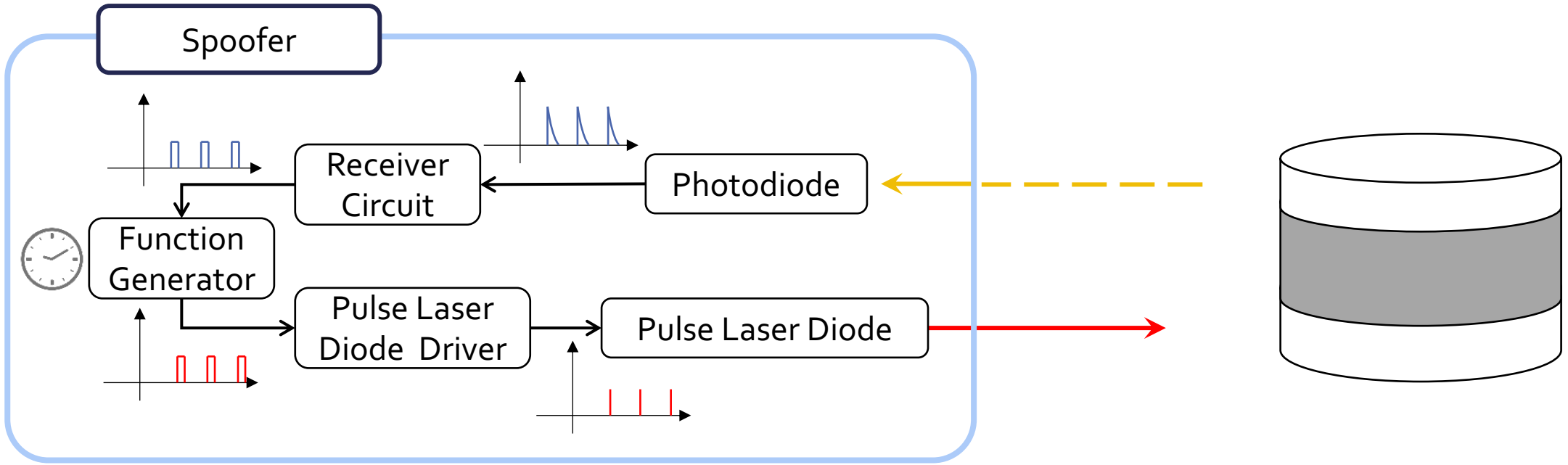

◆Inducing closer fake dots

1. Induce farther dots
2. Reduce the delay in function generator
3. Observe closer dots


Lidar Spoofing of
Multiple Moving Fake Dots

Lidar Spoofing of Fake Dots Closer Than Spoofer

Spoofing by Relaying Attack

- Stealthy against human since IR laser is invisible

- Inducing a farther fake dot
  - Mimic the process
  - Fire laser pulse after positive delay

- Inducing a closer fake dot
  - By the characteristic of lidar, making negative delay is possible

Discussion

- Receiving angle larger than needed
  - Actual receiving angle ≫ Minimum required receiving
  - VLP-16: minimum (0.0048°) vs. actual (2°)
  - Much wider region affected by the attack

Possible Countermeasures and limitations

- Saturation
  - Minimizing receiving angle → reduce the size of affected region
  - Detection is easy
    - Multiple sensors + program to abandon compromised sensor output
    - Alarm, then going into fail-safe mode
  - However, cannot be prevented → none of above is an ultimate solution

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- Spoofing
  - Minimizing receiving angle
  - Adding slight random perturbation to PRTs
    ∵ Random probing is hard to be adopted for current rotating lidars
  - However, induction of single, farther fake dot per spoofer is still possible

Conclusion

- Two types of attack against LiDAR; Saturation, Spoofing

- Saturation
  - Make numerous fake dots using weak light source
  - Make LiDAR completely blind using strong light source
  - Make fake dots in direction other than that of the source

- Spoofing
  - Induce closer fake dots

- Defensive measures exists, but not enough to fully trust LiDAR

Related works

Petit, Jonathan, et al. "**Remote attacks on automated v ehicles sensors: Experiments on camera and lidar**." Bla ck Hat Europe 11.2015 (2015): 995.

- Attack camera-based system and LiDAR
- They successfully blinded camera by emitting light into the camera
- Also, they showed relaying, and spoofing attack against LiDAR

Related works

Yan, Chen, Wenyuan Xu, and Jianhao Liu. "**Can you trust autonomous vehicles: Contactless attacks against sensors of self-driving vehicle**." Def Con 24.8 (2016): 109.

- Attack the ‘eye’ of autonomous vehicles; MMR radar, ultrasonic sensor, cameras
- They showed jamming, spoofing attack on those sensors in Tesla model S

Follow-up works

Sun, Jiachen, et al. "**Towards robust lidar-based perception in autonomous driving: General black-box adversarial sensor attack and countermeasures**." USENIX Security'20.

- Explore vulnerabilities of LiDAR-based perception layer
- With those vulnerability, they constructed black-box spoofing attack
- Suggested defense model CARLO, which detects spoofed data
- Connected sensor spoofing attack to AI model (perception layer)

Questions

Joonha Jang

Q. Tesla announced that it would use "pure vision," which uses only cameras for self-driving cars.

Is 'Pure Vision' really safe?

A. No, even simple backlight can make poor vision.

Questions

Hannah Kim

Q. Has any lidar with random perturbation in PRT came ou t?

A. Currently no one has implemented

KAIST

Thank you for listening

Image sources

Slide 2

CNBC
- https://www.cnbc.com/2021/06/16/alphabets-waymo-raises-2point5-billion-in-new-investment-round.html

TechCrunch
- https://techcrunch.com/2021/11/10/self-driving-truck-startup-kodiak-robotics-raises-125m/
- https://techcrunch.com/2021/11/05/momenta-500-million/
- https://techcrunch.com/2021/04/15/oxbotica-raises-13-8m-from-ocado-to-build-autonomous-vehicle-tech-for-the-online-grocers-logistics-network/

BlueBookServices
- https://www.producebluebook.com/2021/11/02/autonomous-vehicle-delivery-firm-nuro-adds-600mm-investment/#

Slide 11

Electrek
- https://electrek.co/2021/11/11/tesla-tsla-confirms-elon-musk-sold-roughly-5-billion-worth-stock-keep-going/