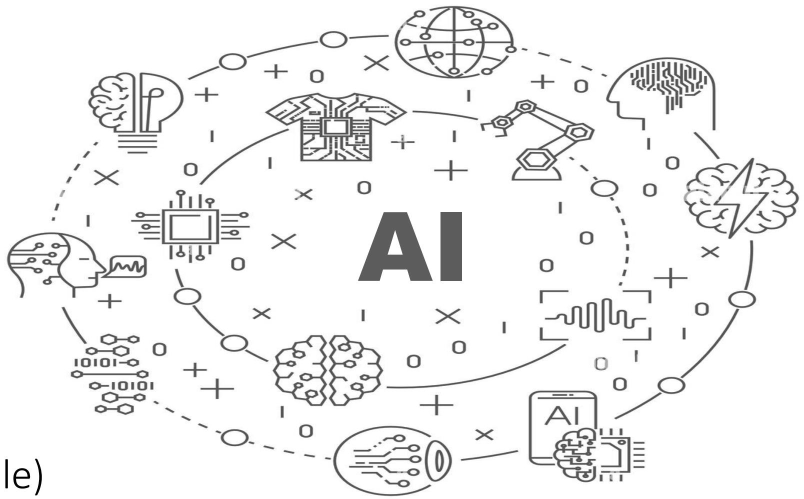
CIS 7000-008: Special Topics on Wireless and Mobile Sensing

Mingmin Zhao (mingminz@cis.upenn.edu)

Lecture 7
Wireless Sensing: Liquid



Penn
University of Pennsylvania

*Some of the slides in this lecture are courtesy of Ashutosh Dhekne (Georgia Tech), Shichao Yue (MIT), and Jian Ding (Yale)

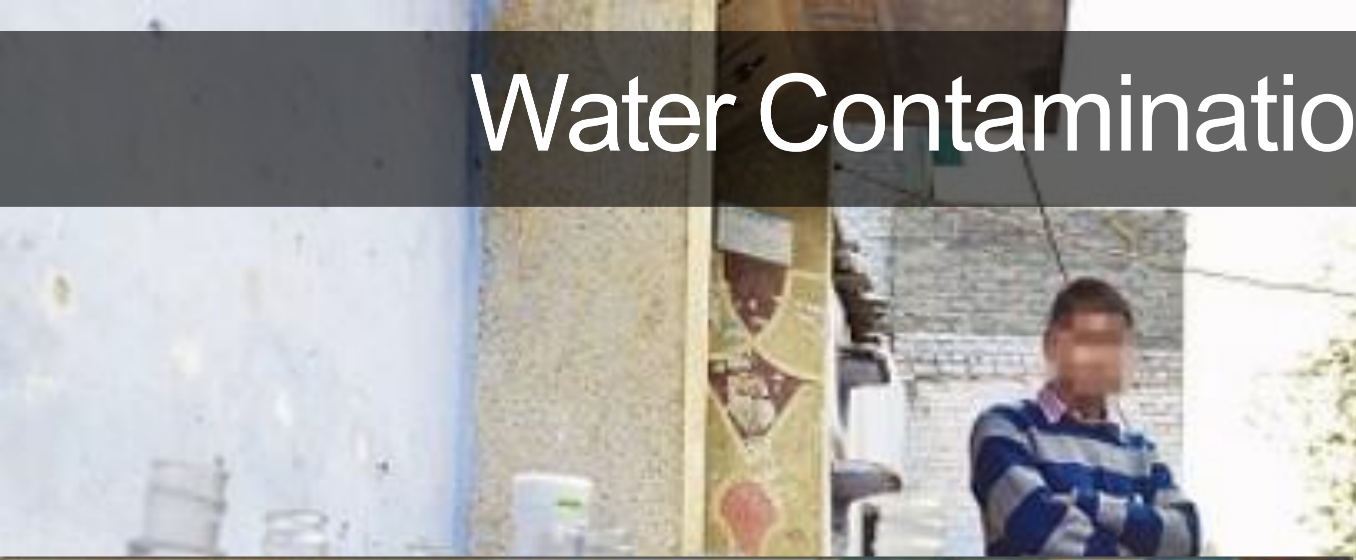
Can we sense food and liquids in closed containers?

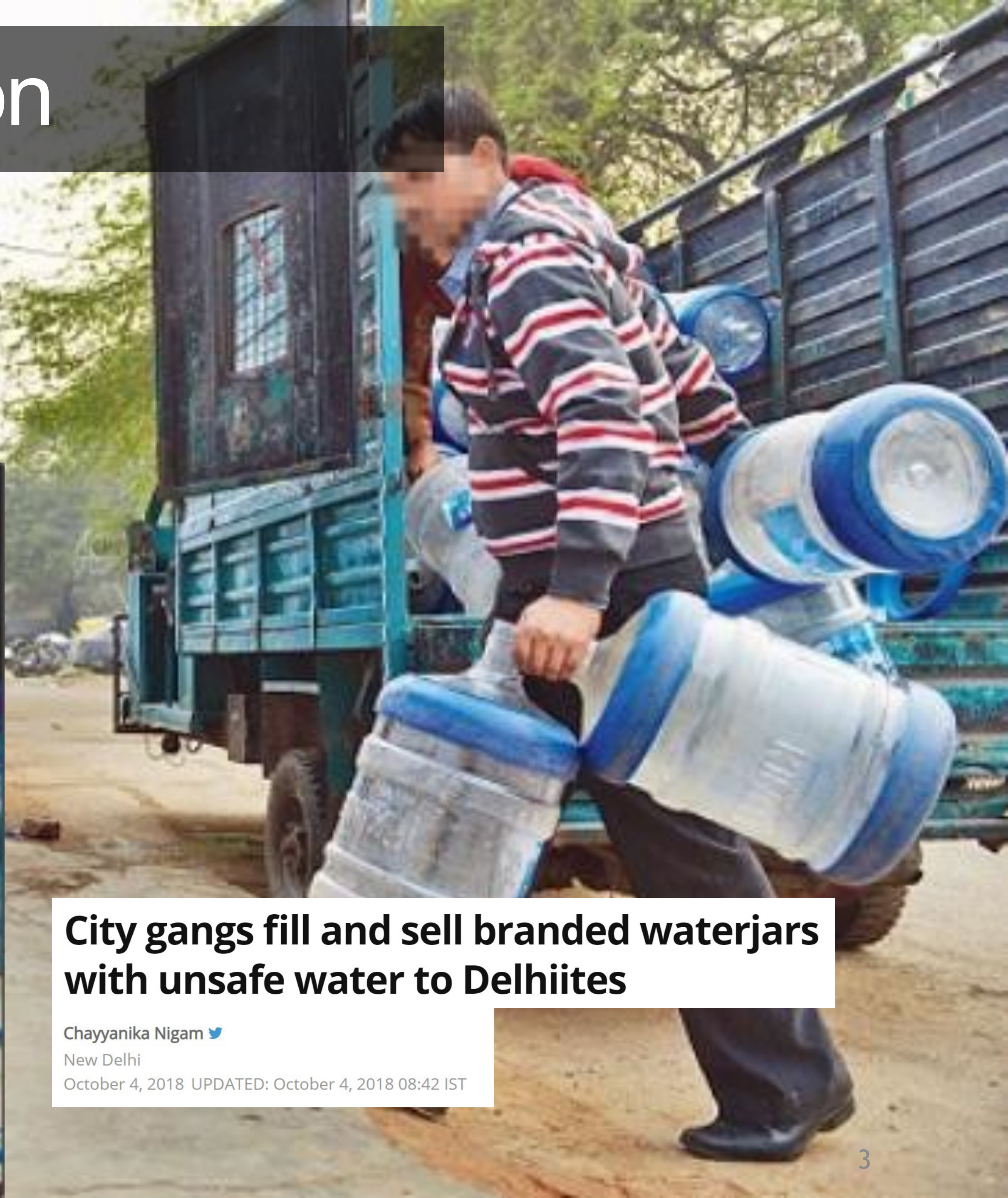
Is it safe?

Is it authentic?

Has it expired?

Water Contamination





City gangs fill and sell branded waterjars with unsafe water to Delhiites

Chayyanika Nigam

New Delhi

October 4, 2018 UPDATED: October 4, 2018 08:42 IST

Airport Security

LiquID: Wireless Sensing Liquids

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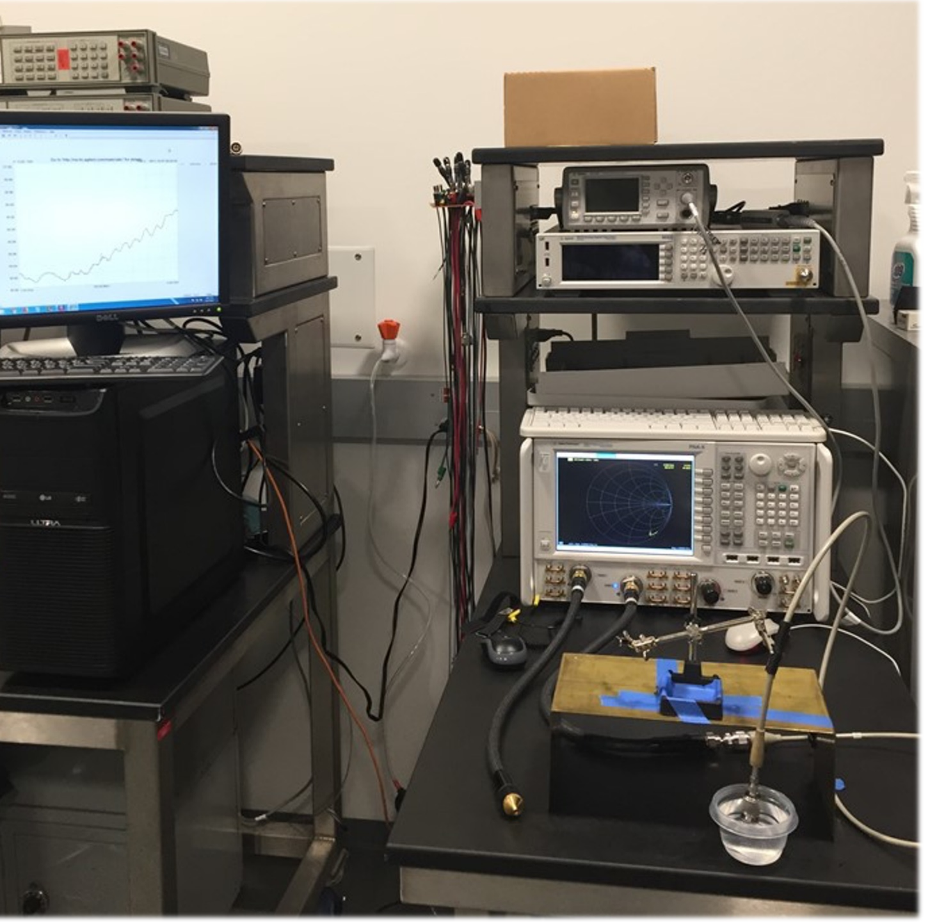
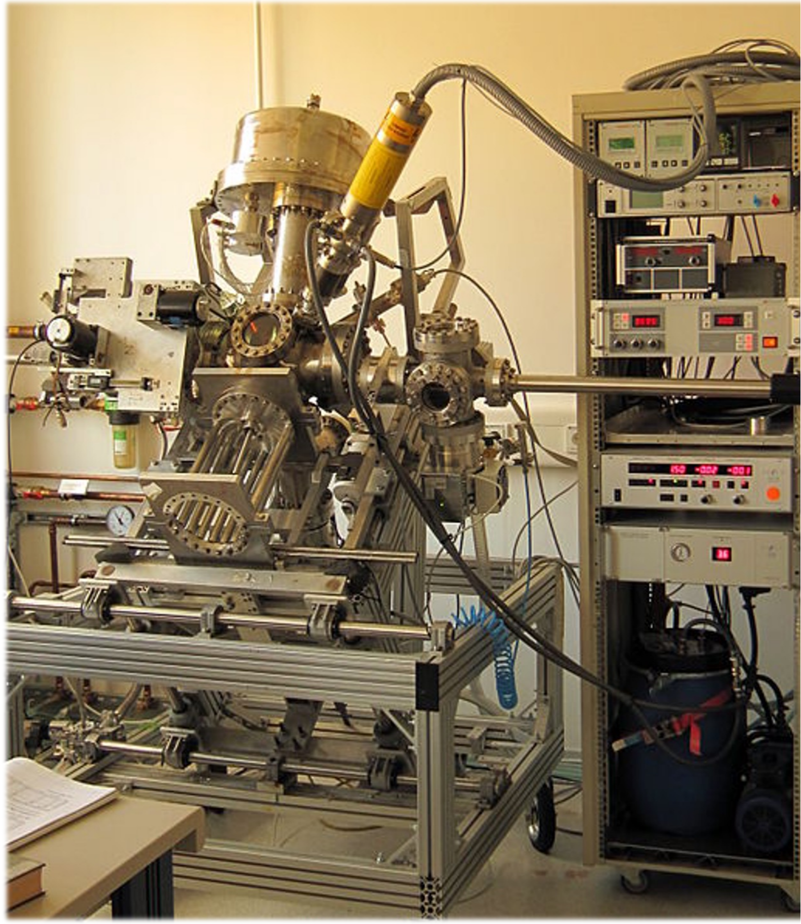
Existing Solutions



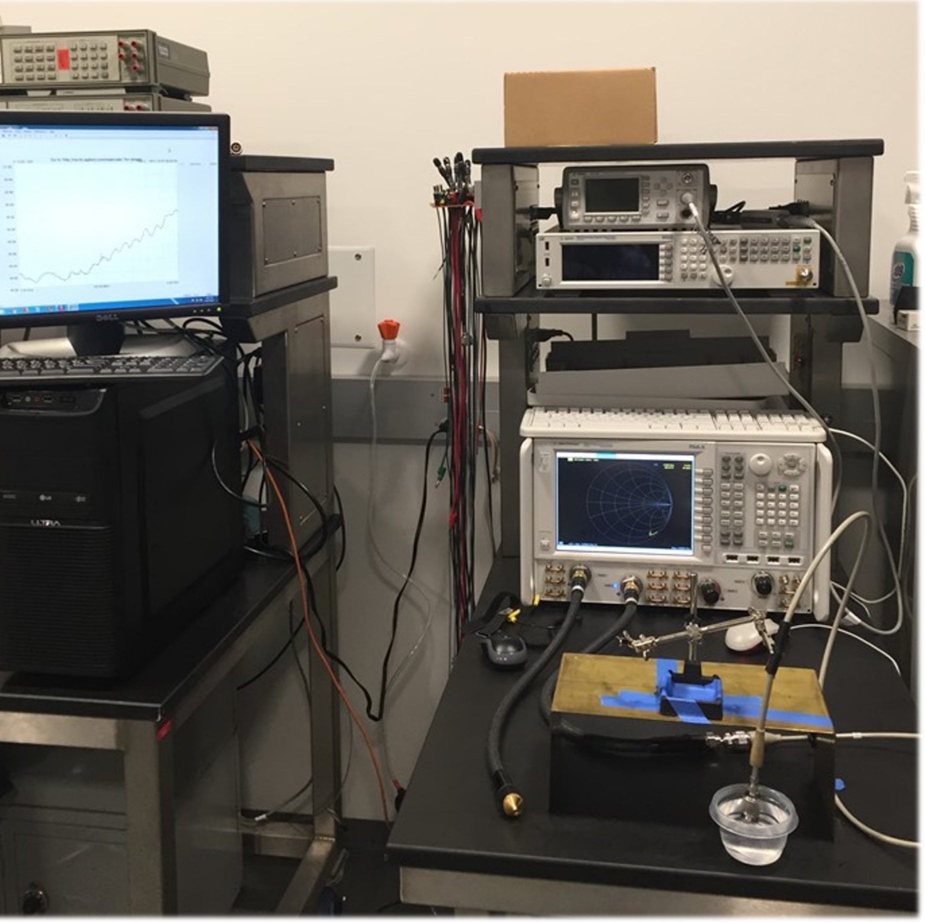


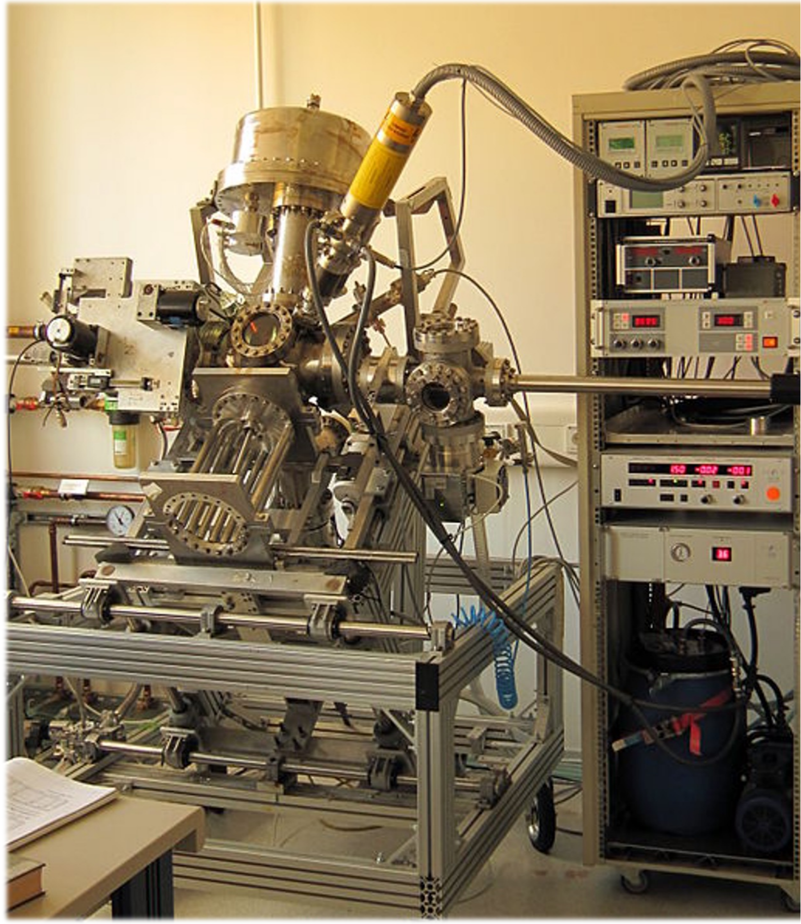
Existing Solutions

Dipping a Probe: Invasive

Chemical Analysis: Destructive

Expensive ($50k +) and Bulky: Inconvenient

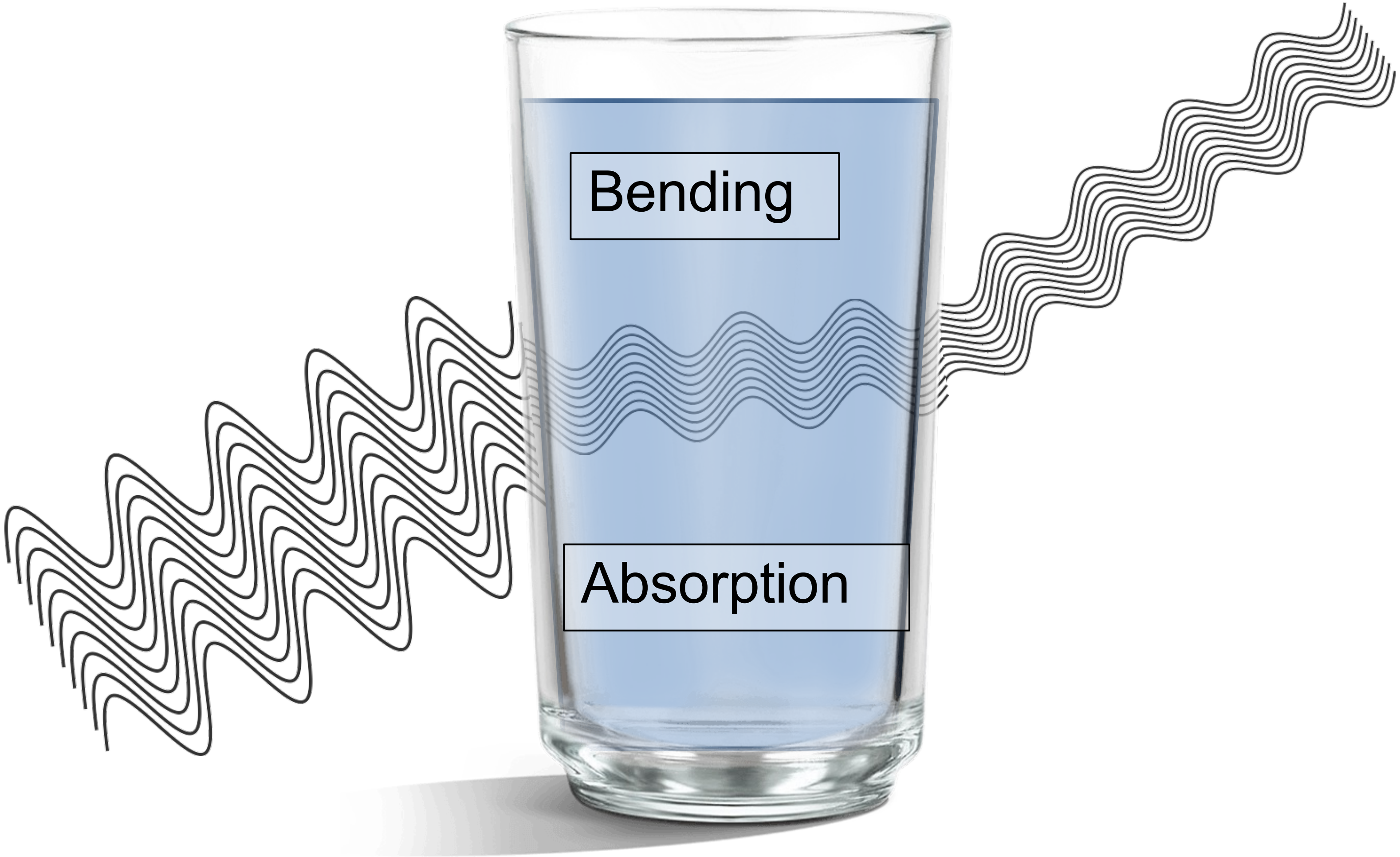




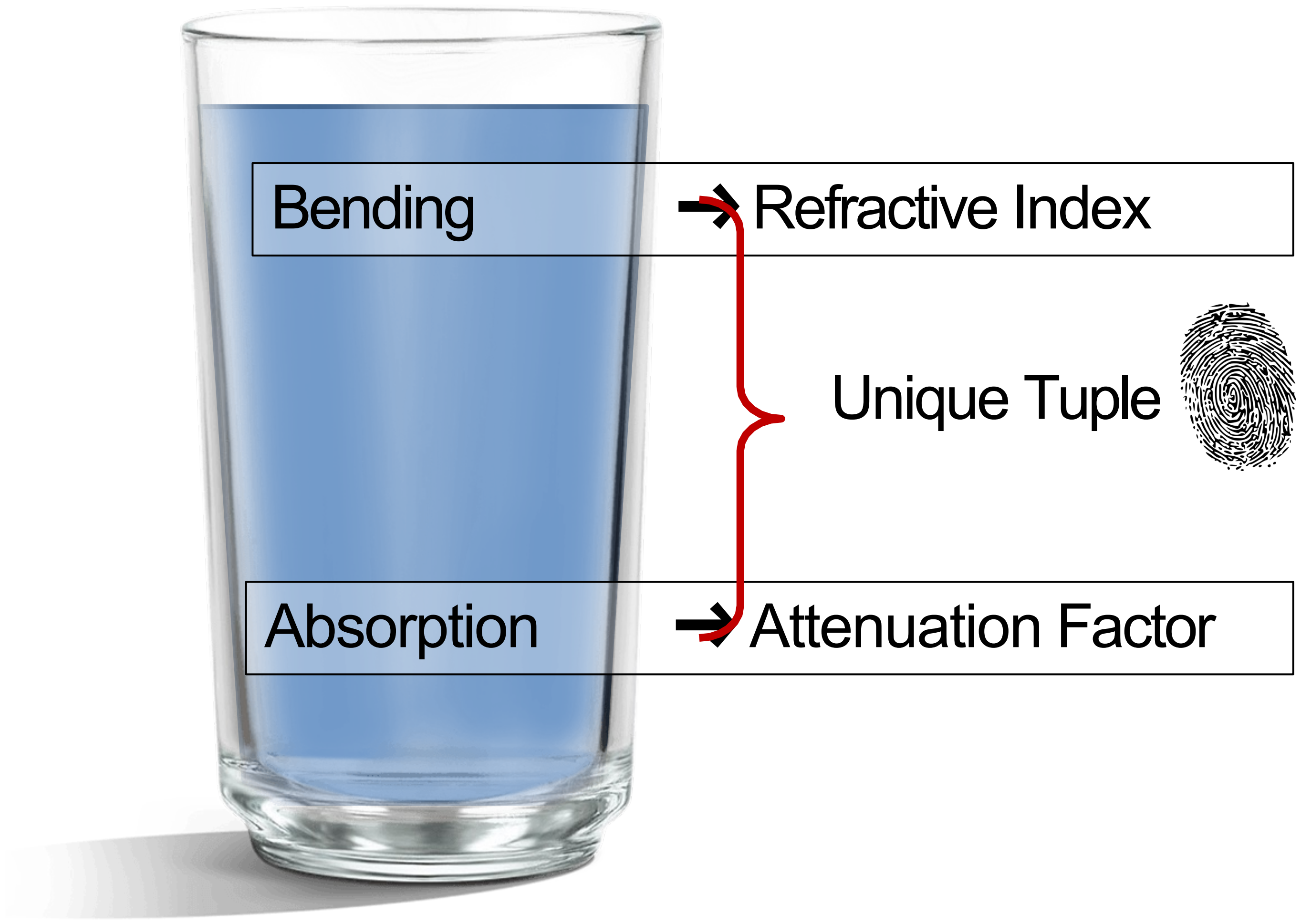
- ✓ Identify liquids without touching it: Non-invasive
- ✓ Using low power, wireless signals: Non-destructive
- ✓ Small and cheap: IoT

How ?

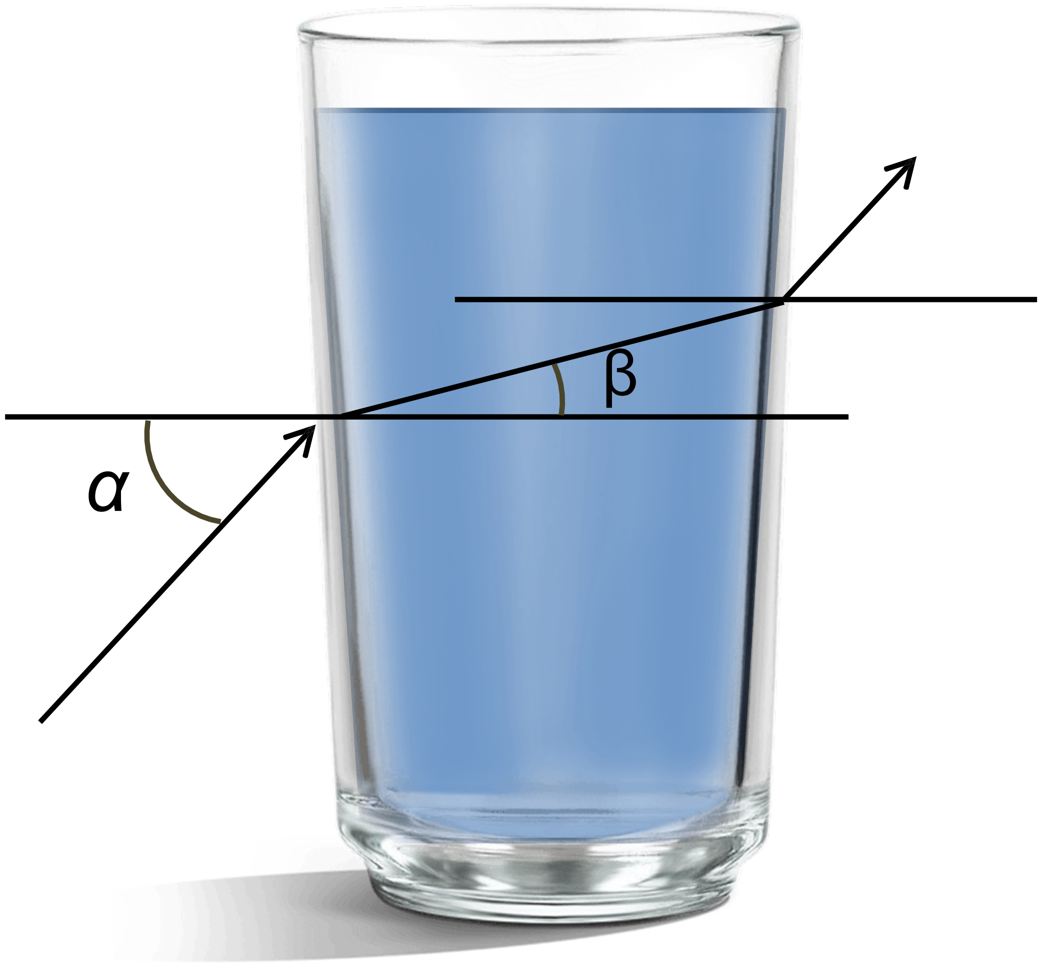
Key Properties of Liquid



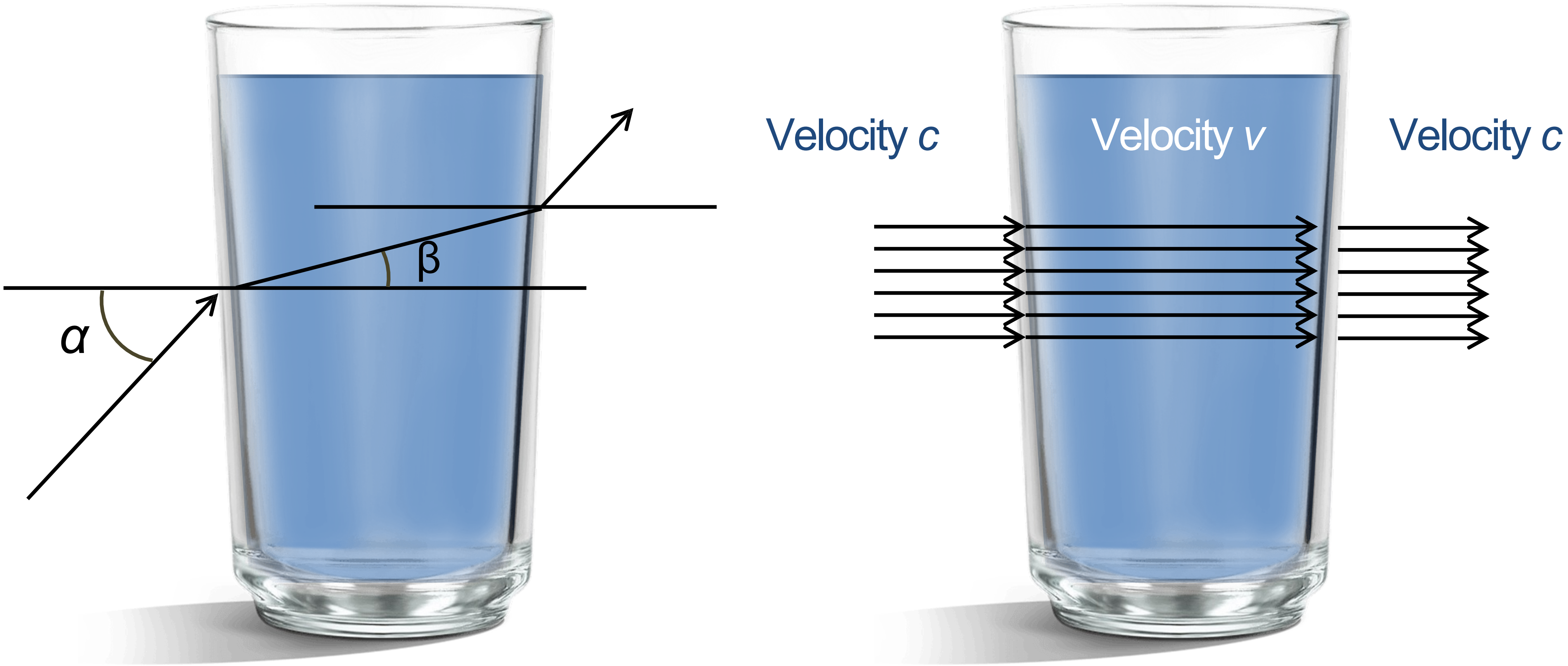
Key Properties of Liquid



$$\text{Refractive Index} = \frac{\sin\alpha}{\sin\beta}$$

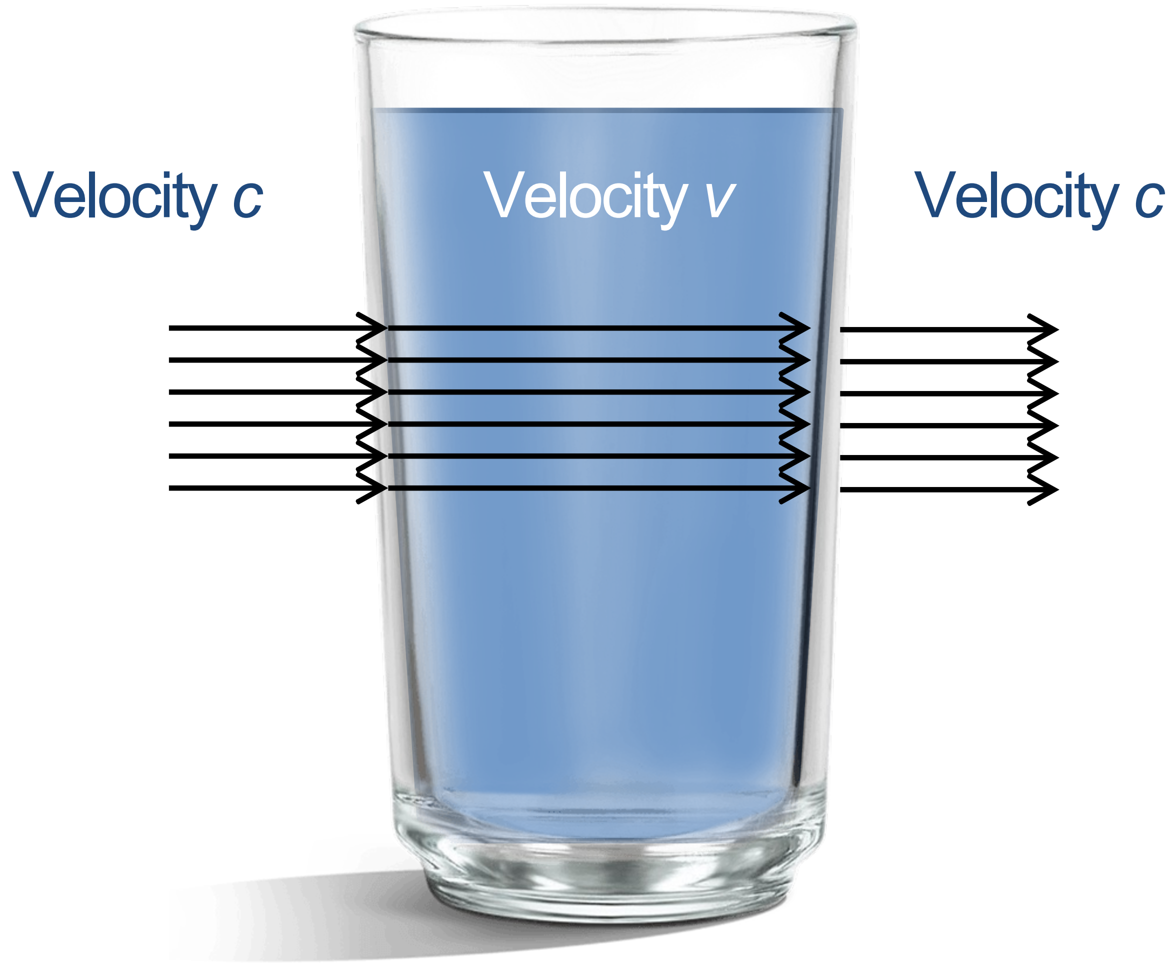


$$\text{Refractive Index} = \frac{\sin\alpha}{\sin\beta} = \frac{c}{v}$$



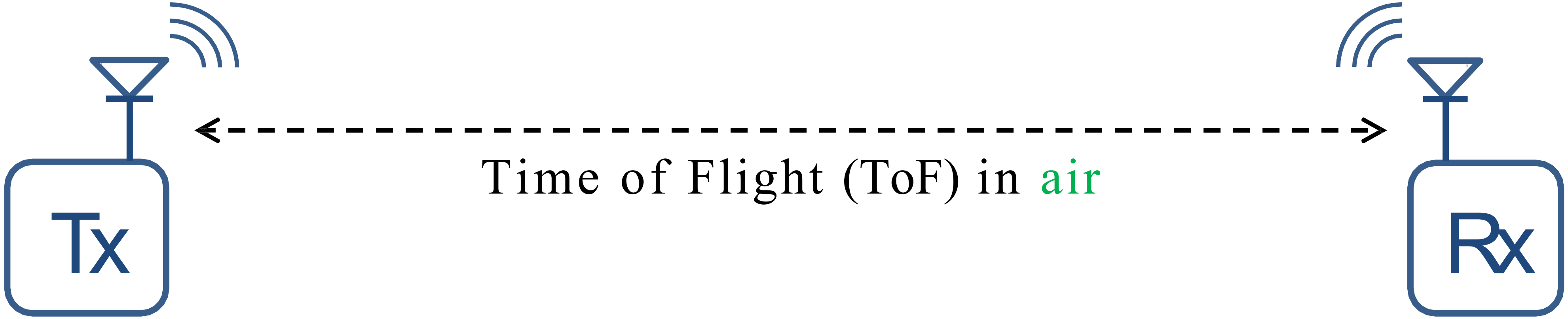
$$\text{Refractive Index} = \frac{\sin\alpha}{\sin\beta} = \frac{c}{v}$$

Measure "slow-down"

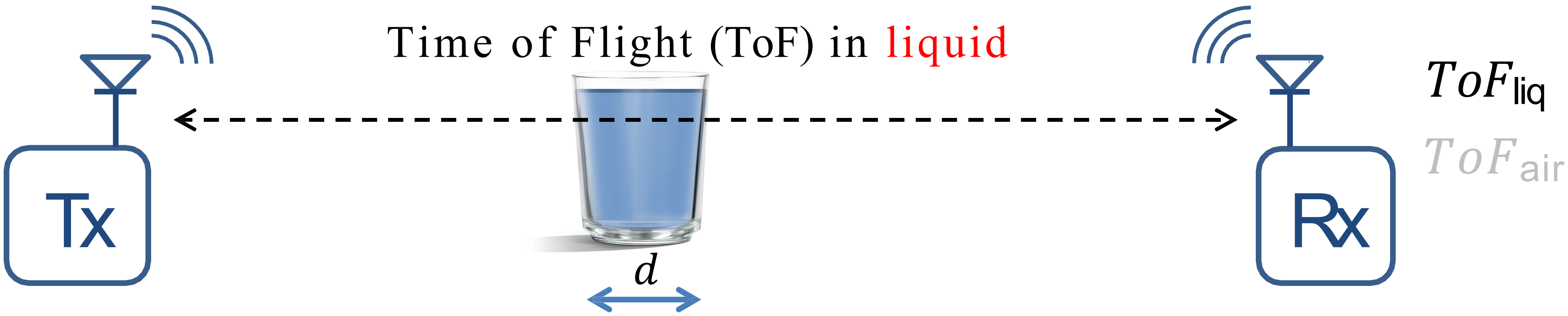


How to measure slow down ?

In principle, this is simple …

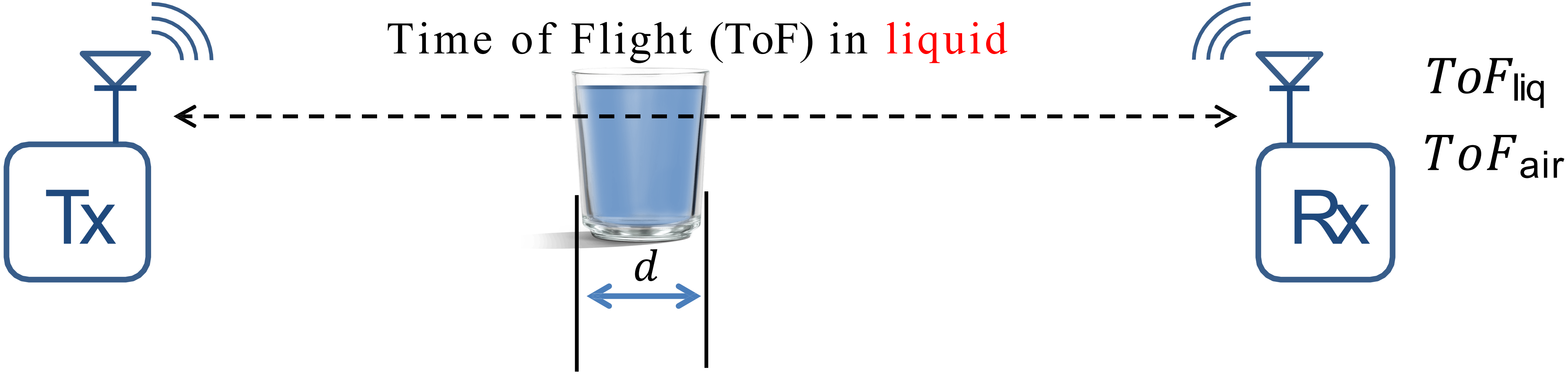


ToF_{air}



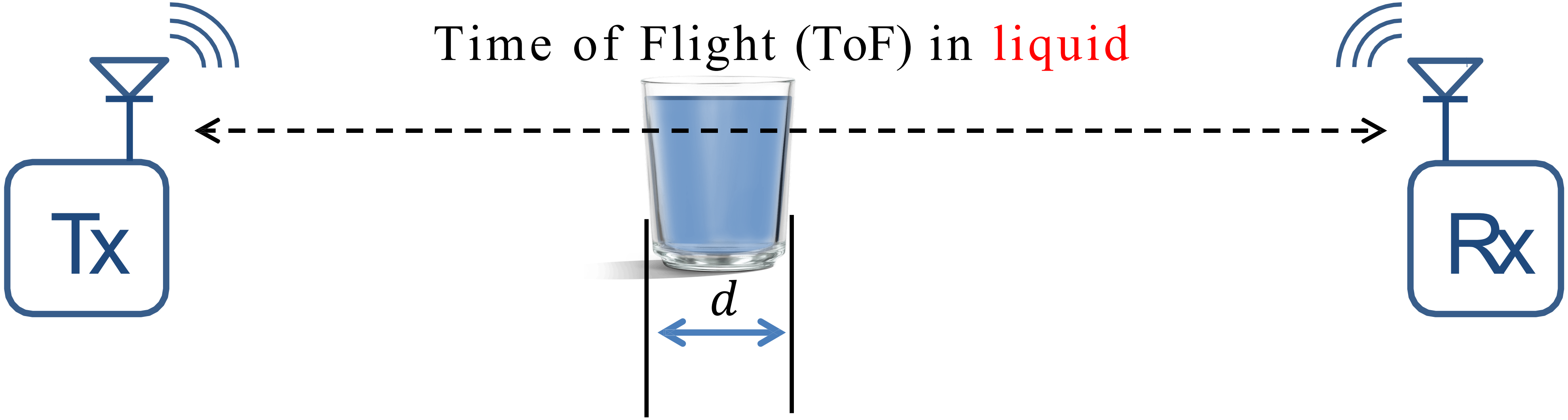
Time of Flight (ToF) in liquid
Tx
Rx
d
ToF_{liq}
ToF_{air}

Time of Flight (ToF) in liquid



$$ToF_{\text{liq}} - ToF_{\text{air}} = \frac{d}{v} - \frac{d}{c}$$

Time of Flight (ToF) in liquid



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So how can we measure these 2 ToFs?

$$ToF_{\text{liq}} - ToF_{\text{air}} = \frac{d}{v} - \frac{d}{c}$$

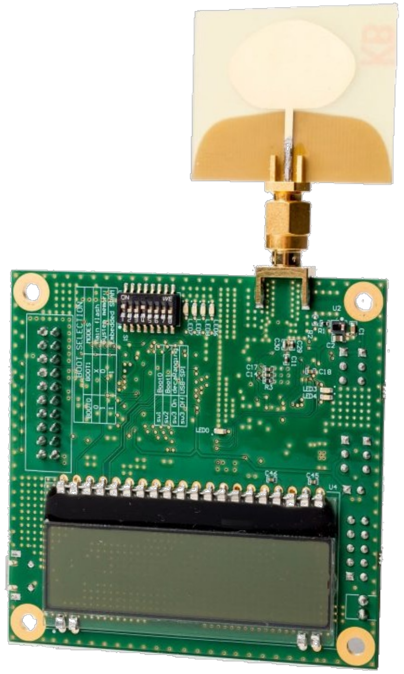
$$Refractive\ Index = \frac{c}{v}$$

So how can we measure these 2 ToFs?

Current state of the art …

Ultra-wideband (UWB) Radios

- Inexpensive
- 1GHz of bandwidth
- Perform signal processing
- Achieves ToF at nanosecond granularity

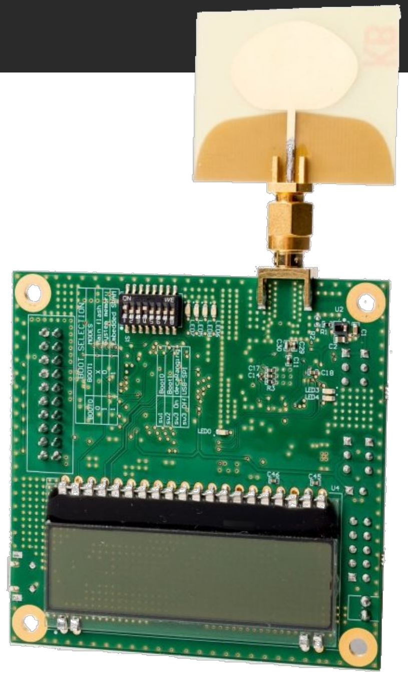


Decawave Trek1000

$$ToF_{\text{liq}} - ToF_{\text{air}} = \frac{d}{v} - \frac{d}{c}$$

$$Refractive\ Index = \frac{c}{v}$$

Is nanosecond good enough ?



$$ToF_{\text{liq}} - ToF_{\text{air}} = \frac{d}{v} - \frac{d}{c}$$

$$Refractive\ Index = \frac{c}{v}$$

Is nanosecond good enough ?

−

≈

nature electronics — 267.5 GHz

Article | Published: 13 July 2018

An on-chip fully electronic molecular clock based on sub-terahertz rotational spectroscopy

Cheng Wang, Xiang Yi, James Mawdsley, Mina Kim, Zihan Wang & Ruonan Han

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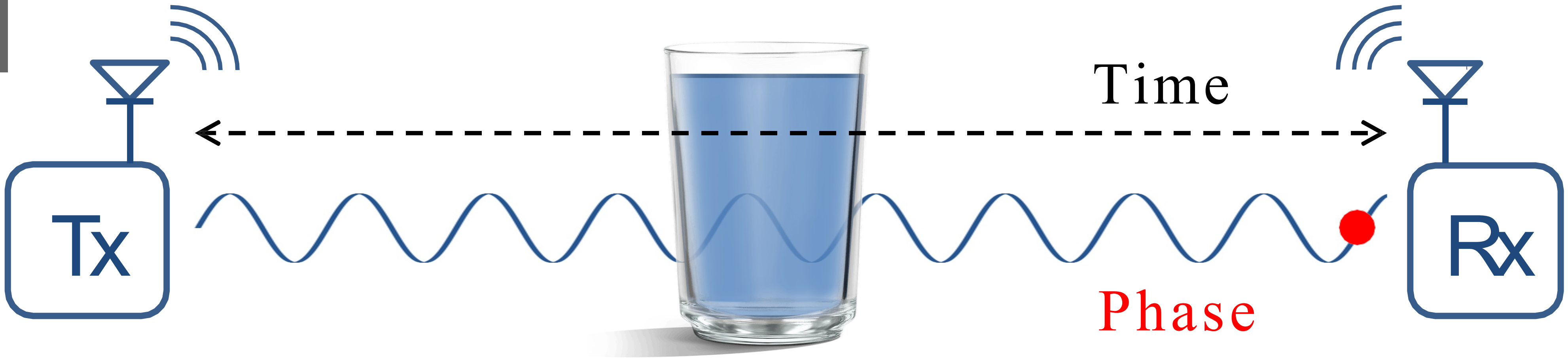
≈ 1 nanosec.

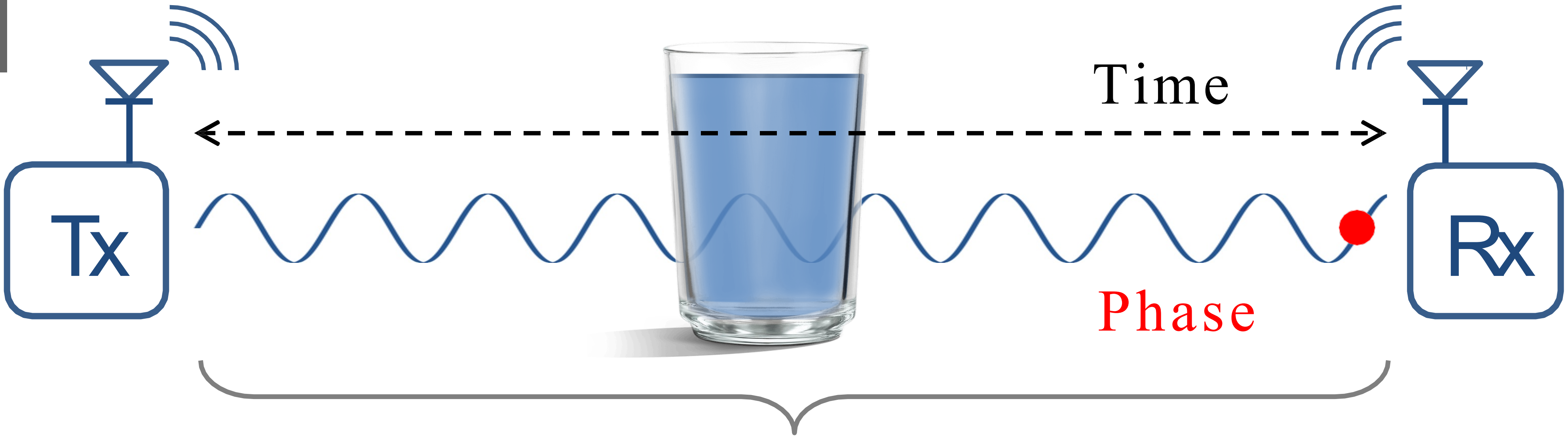
Absolute ToF difficult at picoseconds

Nanosec. gives coarse grained estimate … useful but not sufficient

Phase

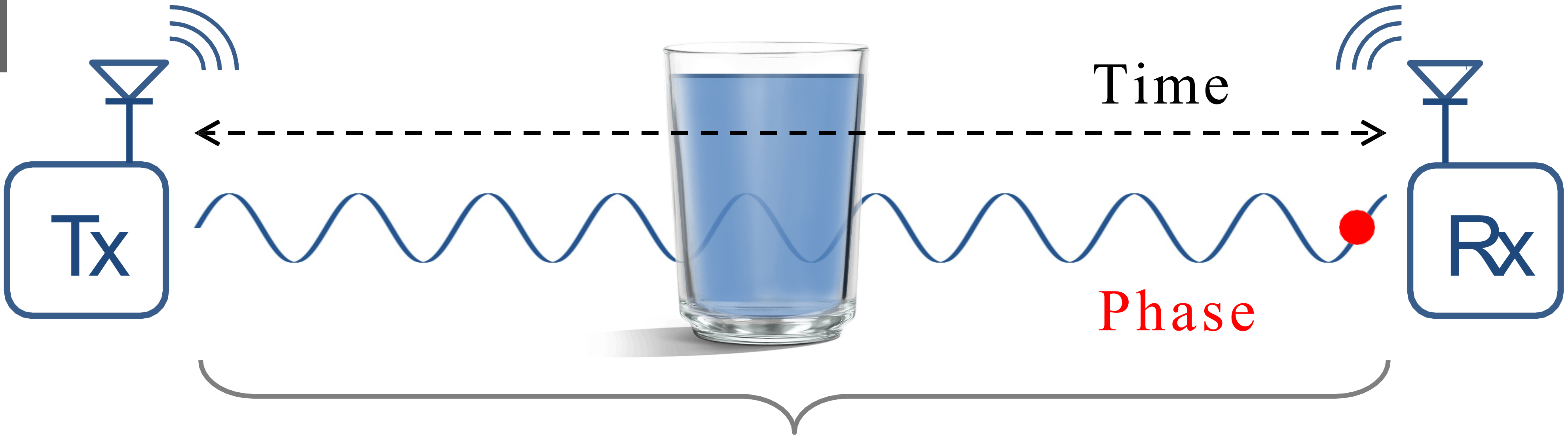


Phase



Distance $d = N\lambda + \phi$

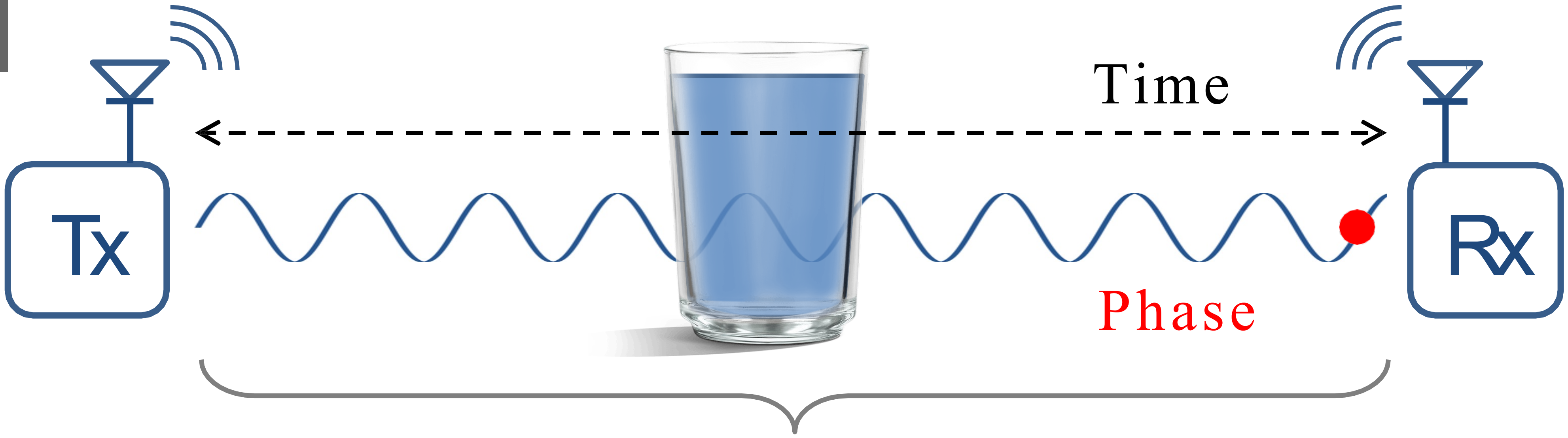
Phase



Distance $d = N\lambda + \phi$

and ϕ measurable in very high resolution ...

Phase

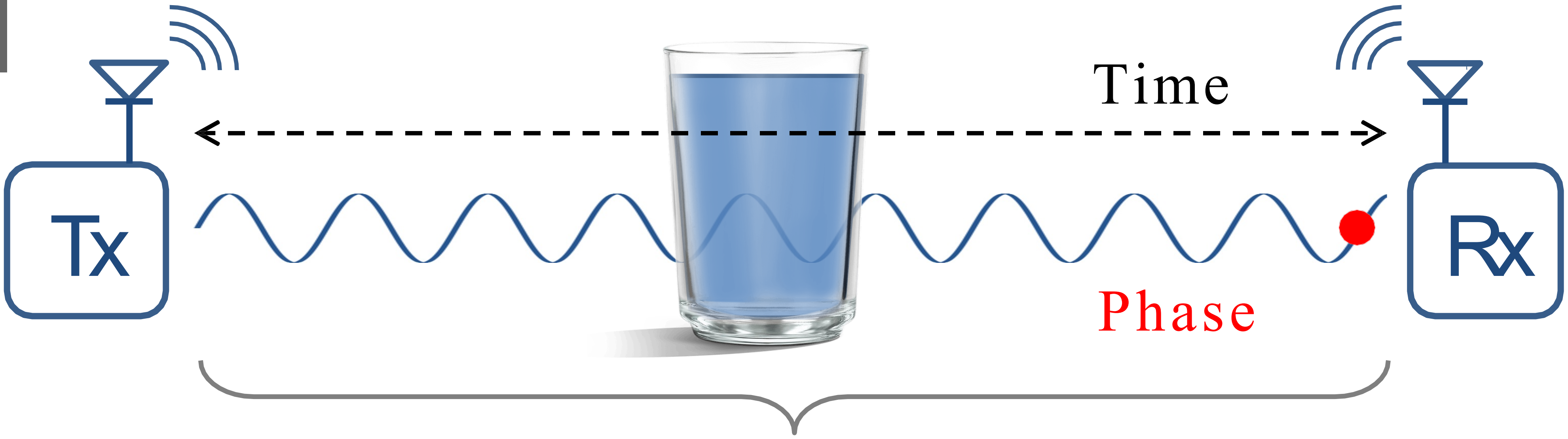


Distance $d = N\lambda + \phi$

and ϕ measurable in very high resolution …

Hence, an opportunity to combine ToF + Phase to estimate slowdown

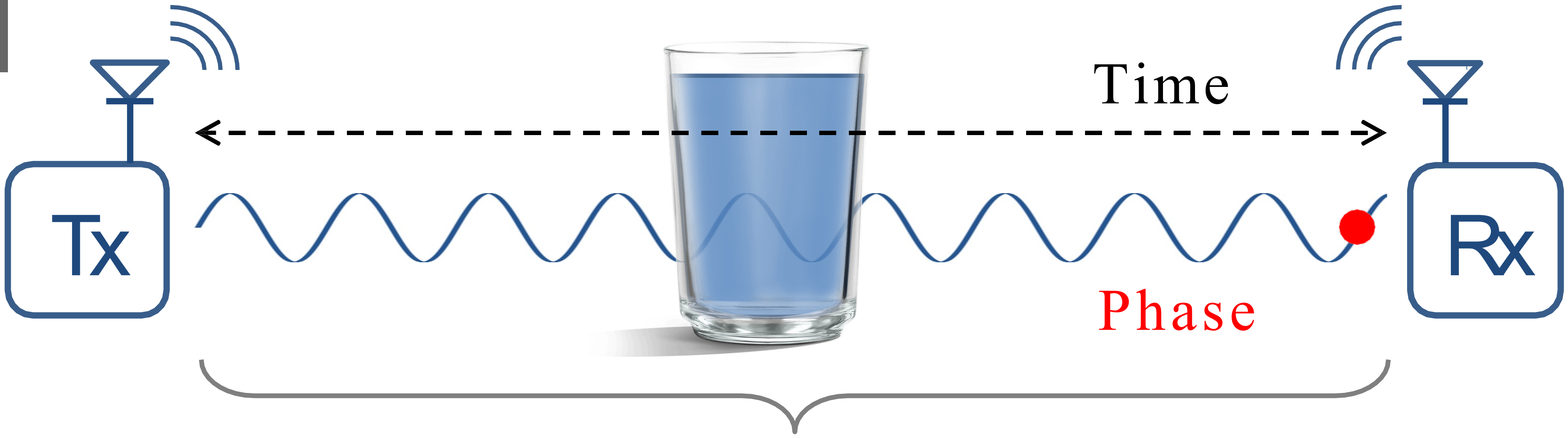
Phase



Distance $d = N\lambda + \phi$

But, no free lunch → phase presents 2 key problems

Phase



Distance $d = N\lambda + \phi$

But, no free lunch ➔ phase presents 2 key problems

Initial phase unknown

N is unknown

But, no free lunch → phase presents 2 key problems

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✓ Possible to solve by combining with time (ToF)

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Difficult because every transmission has arbitrary initial phase

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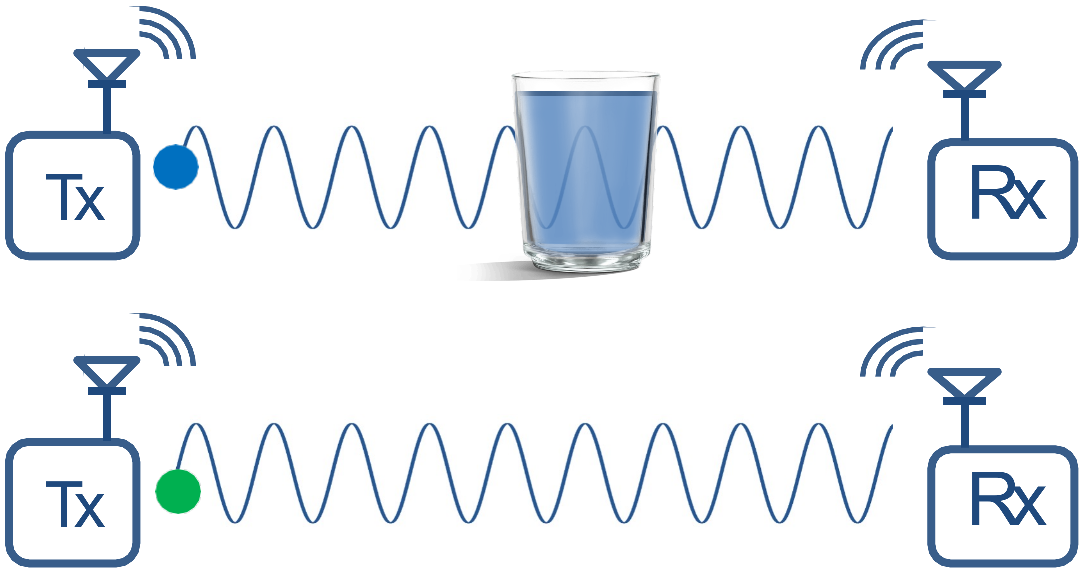
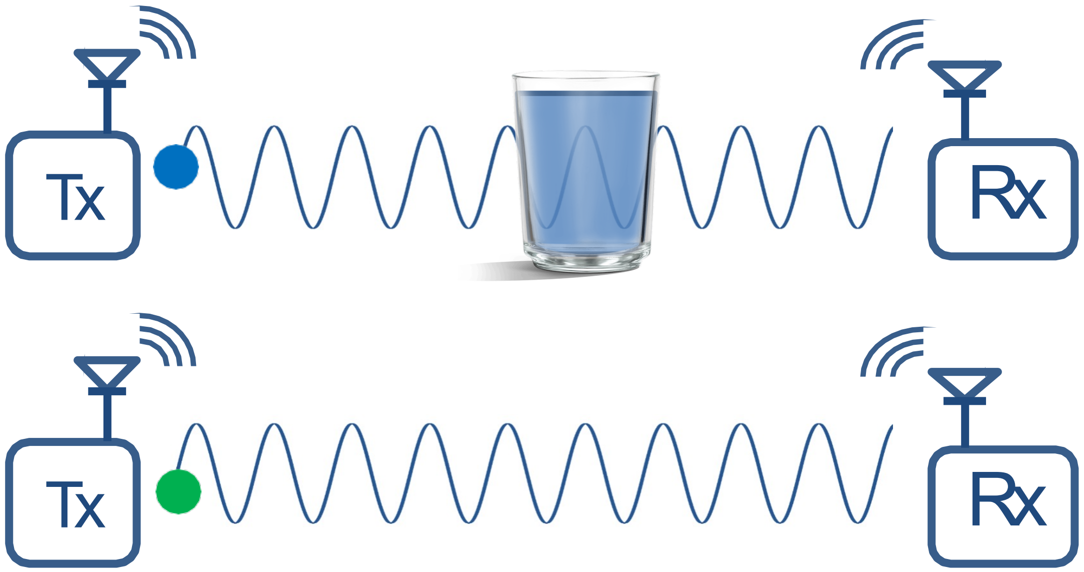


N is unknown

✓ Possible to solve by combining with time (ToF)

But we only care about relative phases = $\phi_{liq} - \phi_{air}$



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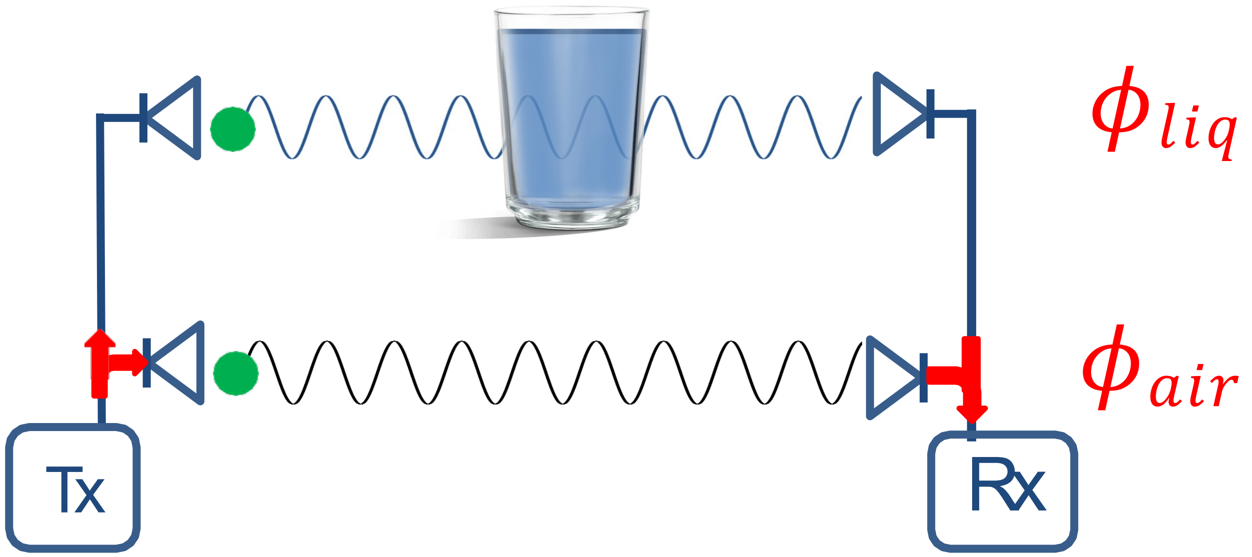
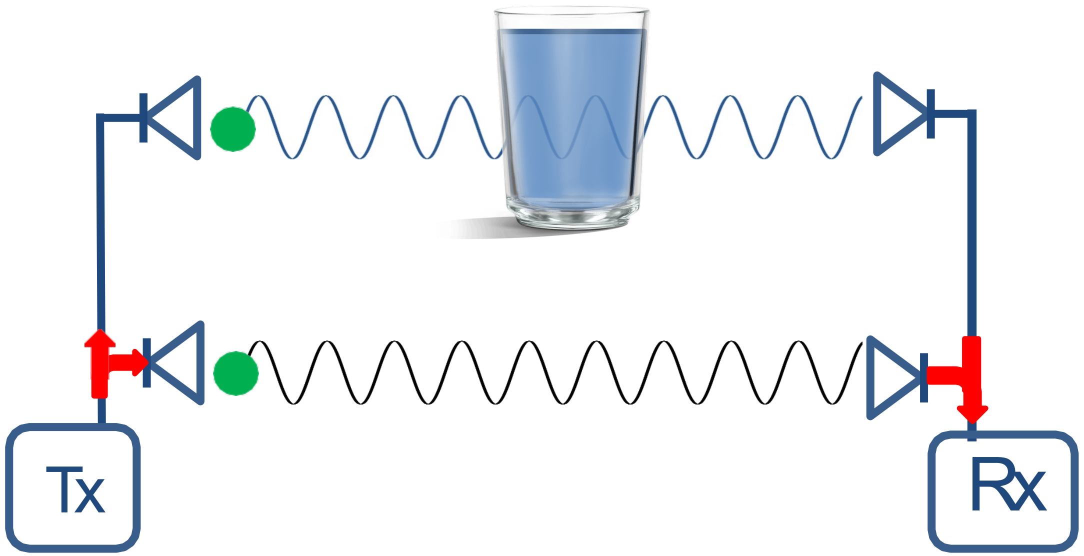


But we only care about relative phases = $\phi_{liq} - \phi_{air}$

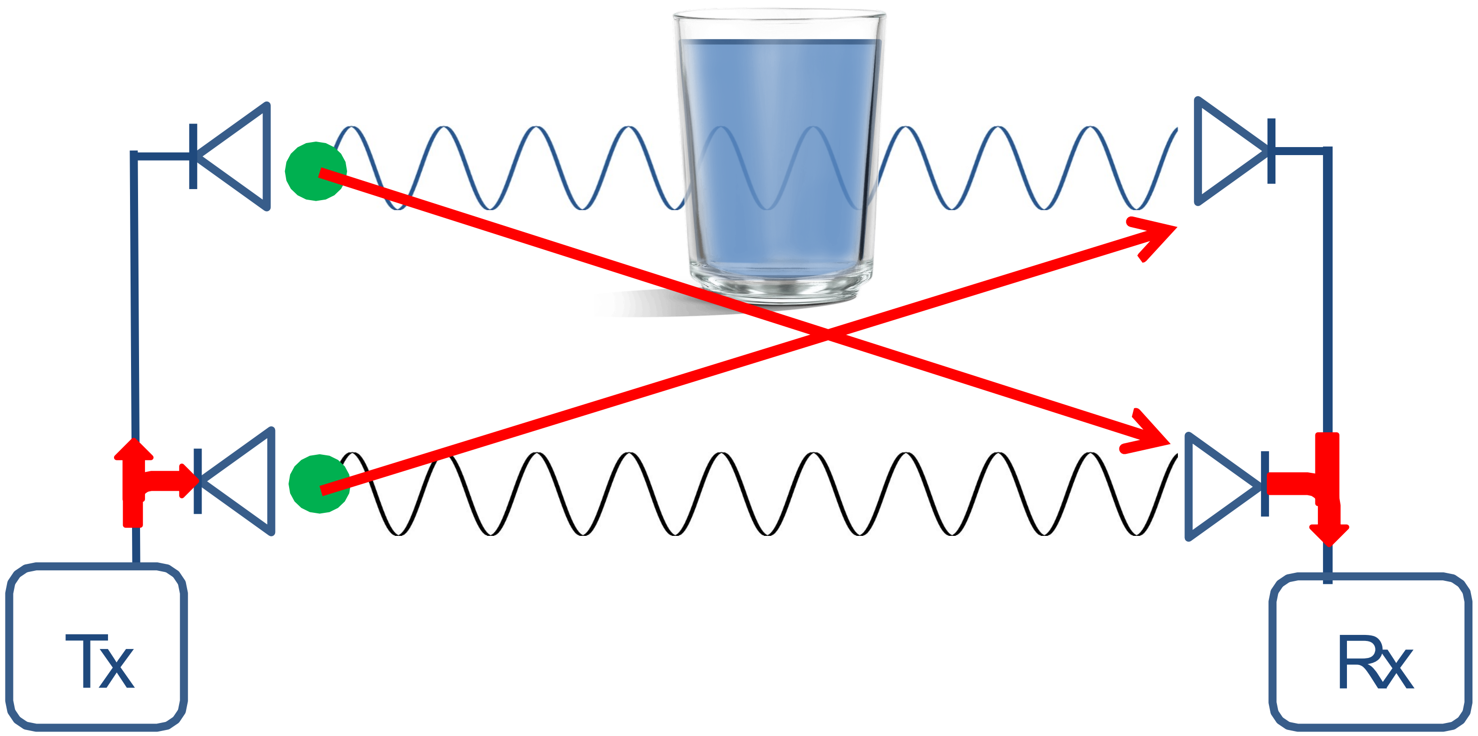
So, we create a parallel measurement …

And cancel the initial phase by subtraction



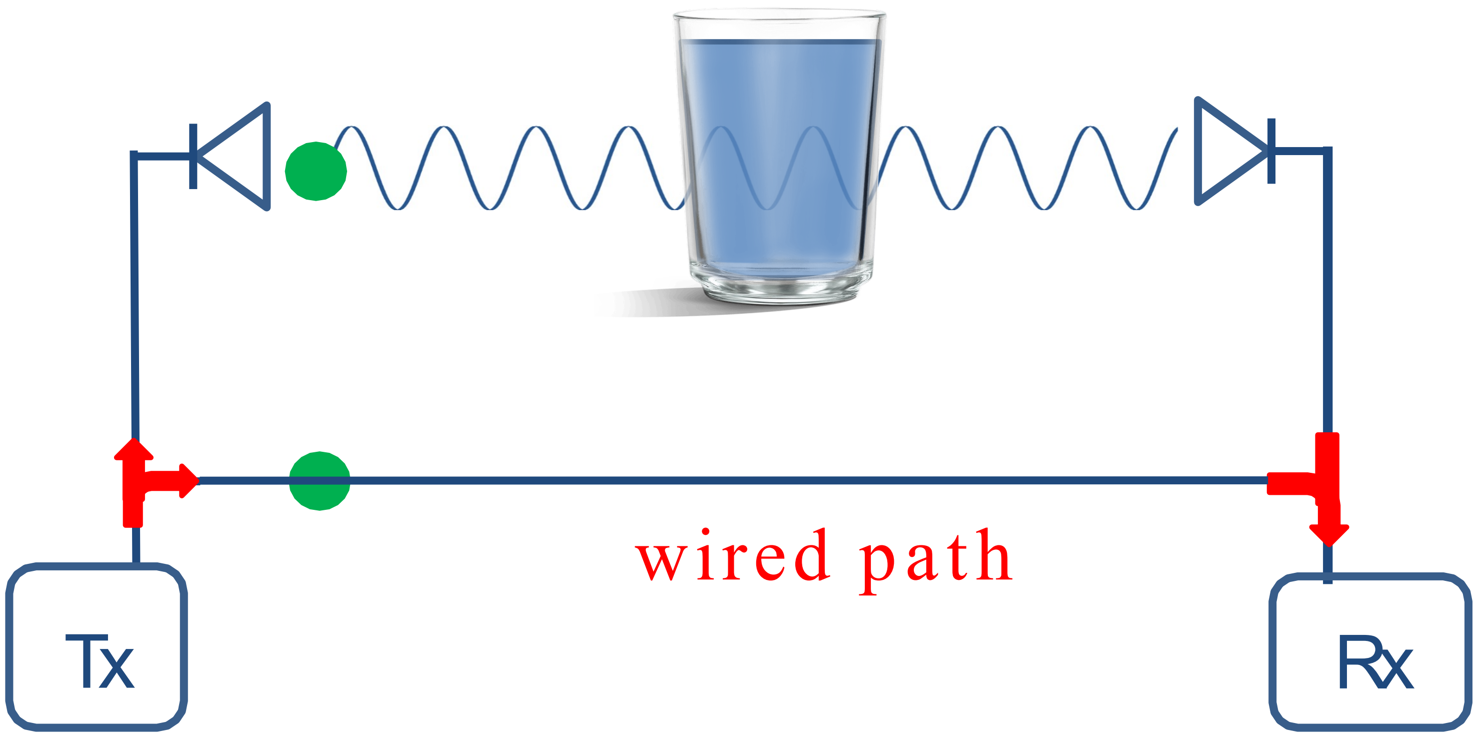
$\phi_{liq} - \phi_{air}$

But nearby antennas create cross talk



But nearby antennas create cross talk

So we create a wired path as a new baseline



Summarizing what we have thus far…

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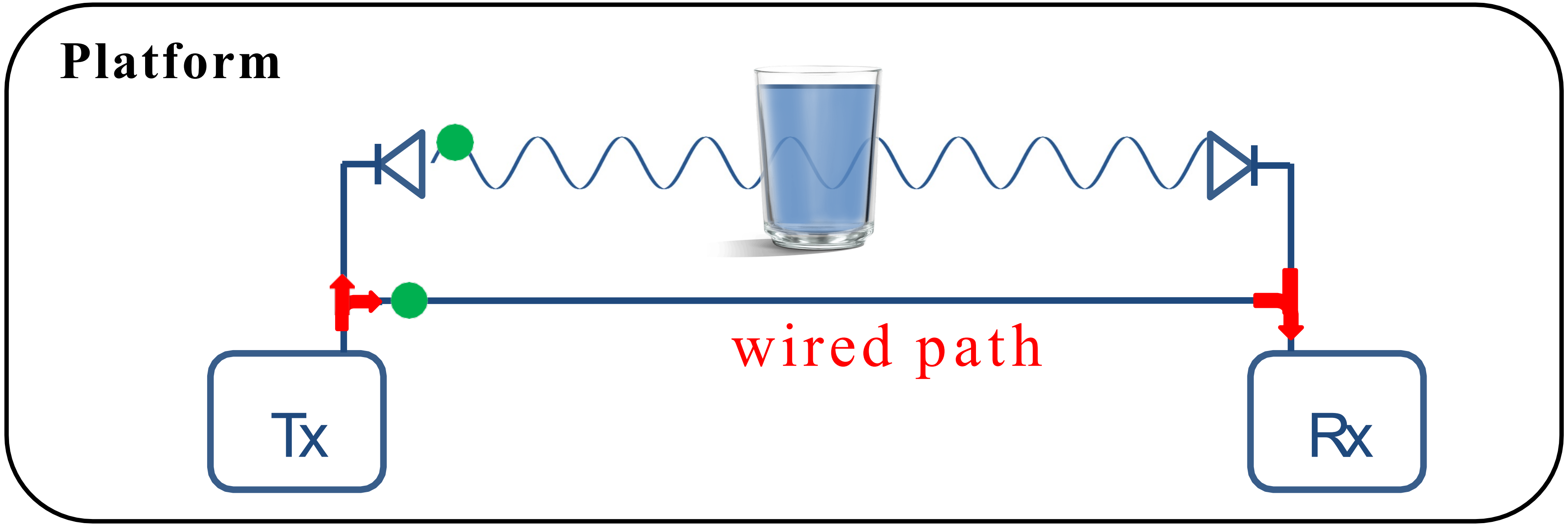


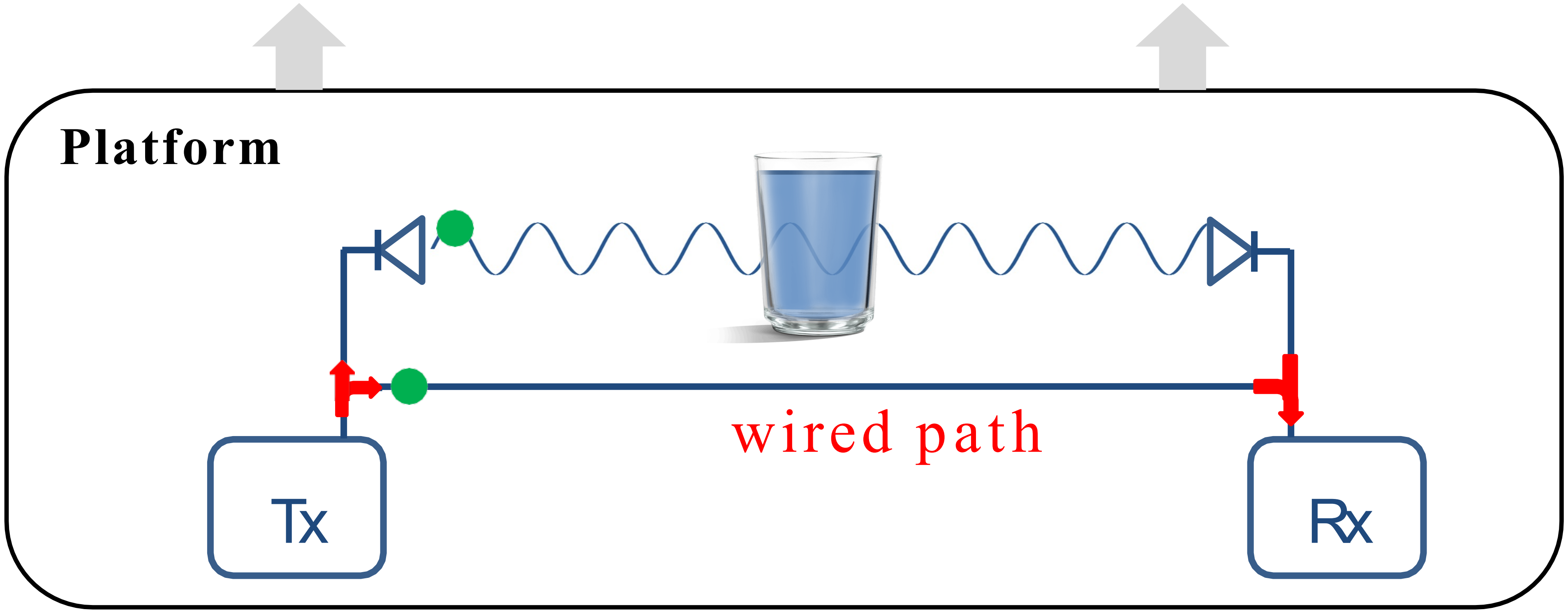
Summarizing what we have thus far…

Nanoseconds

$$ToF_{liq} - ToF_{wire} = \Delta T_{wire}^{liq}$$

Picoseconds

$$\phi_{liq} - \phi_{wire} = \Delta\phi_{wire}^{liq}$$



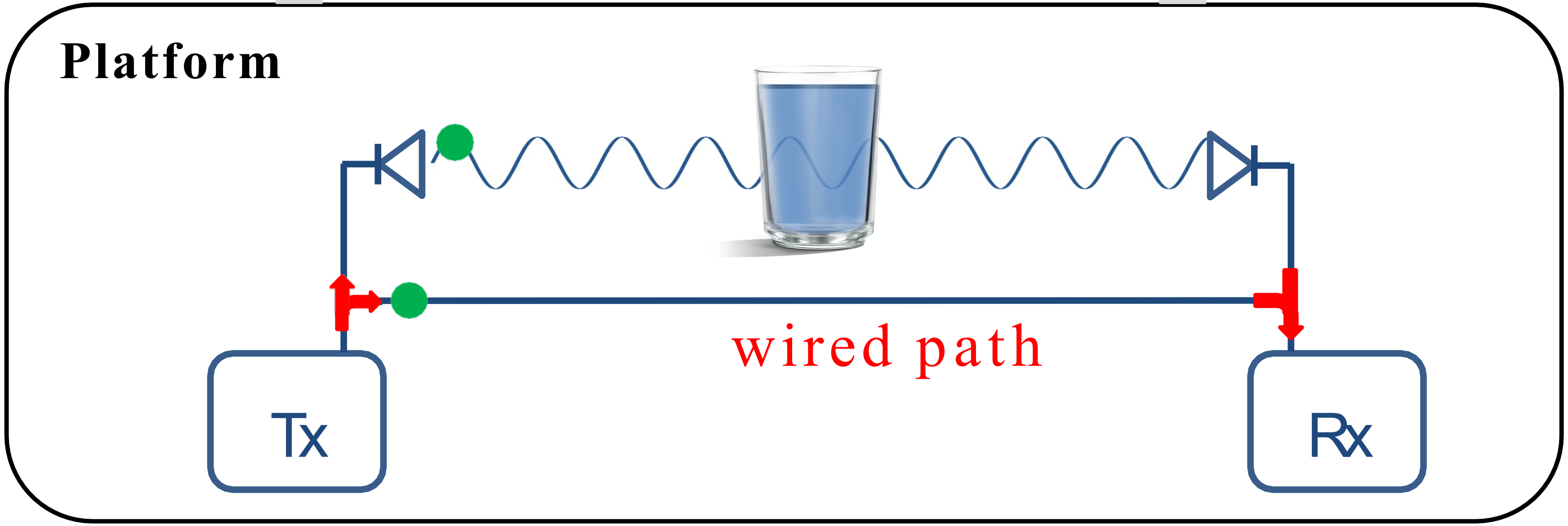
Fuse time + phase → Refractive index

Nanoseconds

$$ToF_{liq} - ToF_{wire} = \Delta T_{wire}^{liq}$$

Picoseconds

$$\phi_{liq} - \phi_{wire} = \Delta\phi_{wire}^{liq}$$

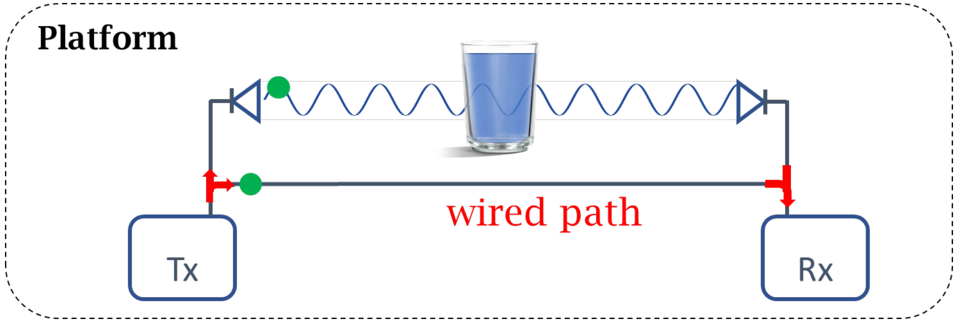


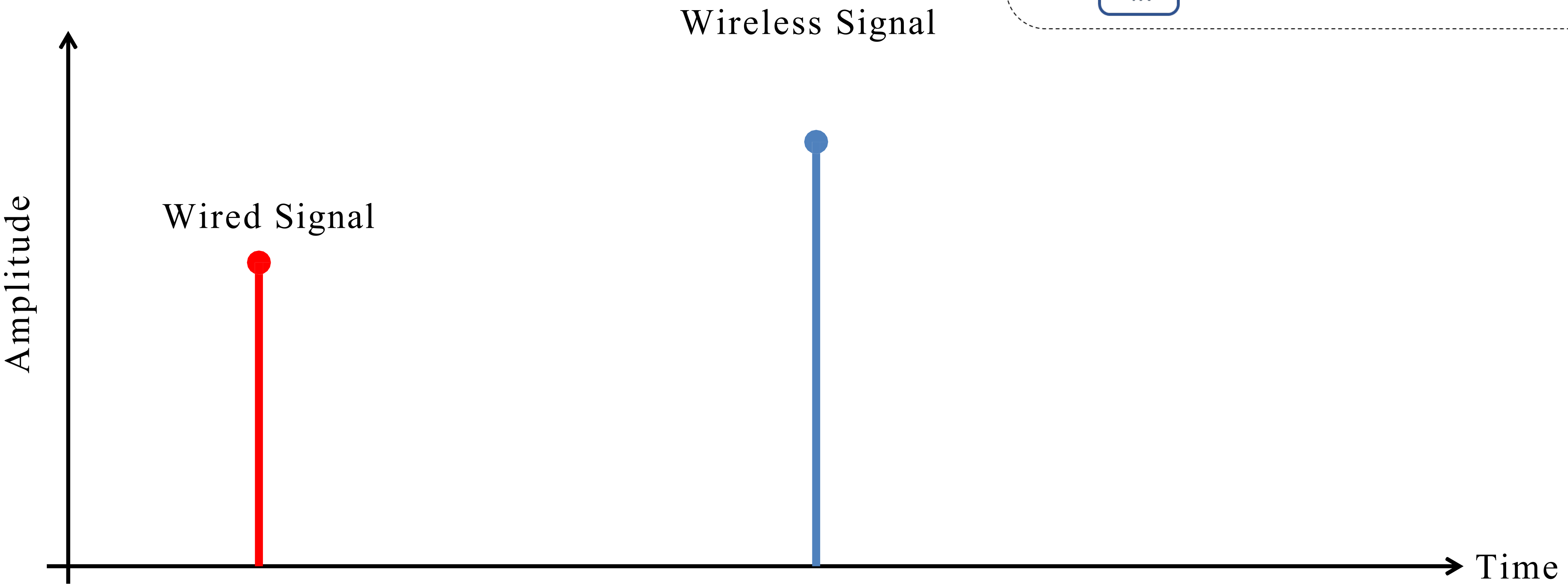
We have an idealized sketch of the solution …

Let’s now turn to practice …

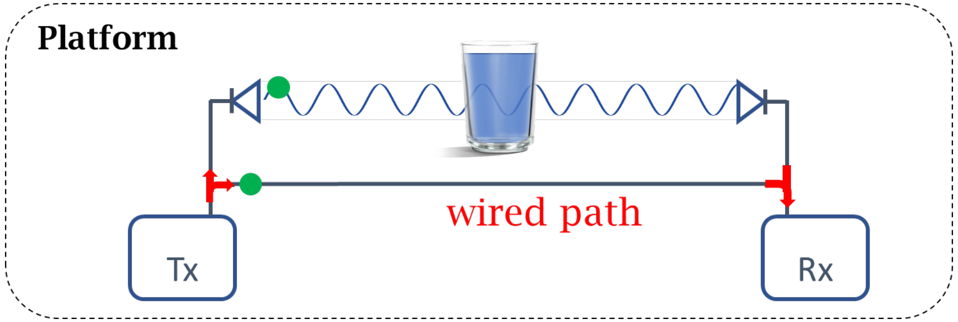
with real radios and environments

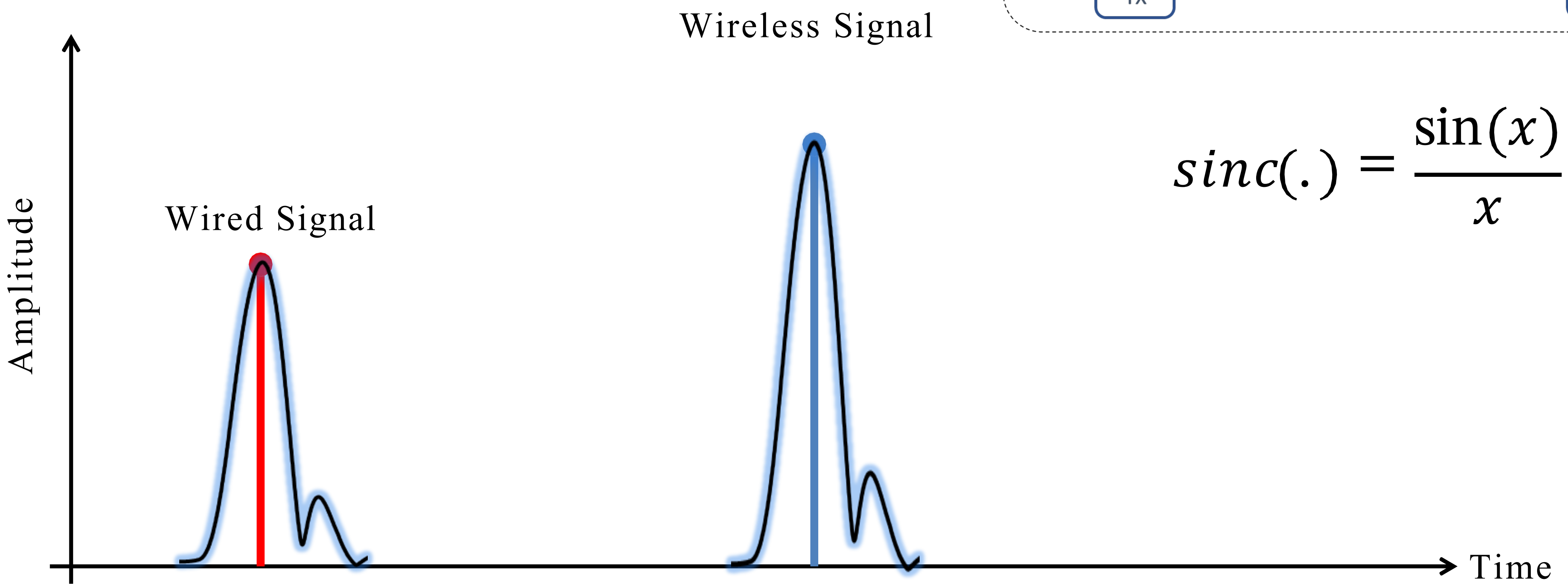
Ideally, at the Receiver…





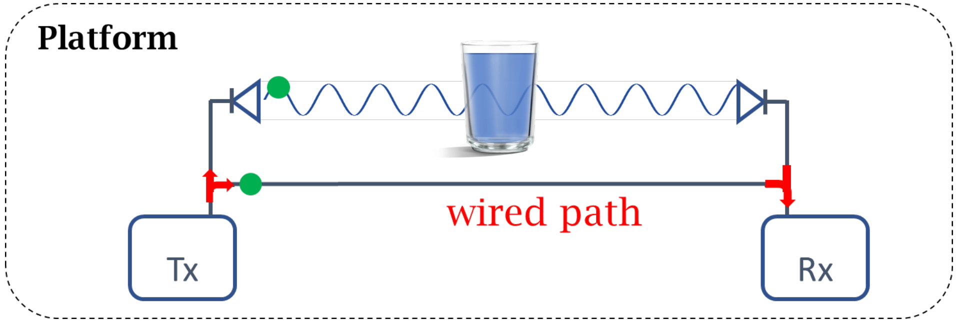
Practical Hardware causes Distortions

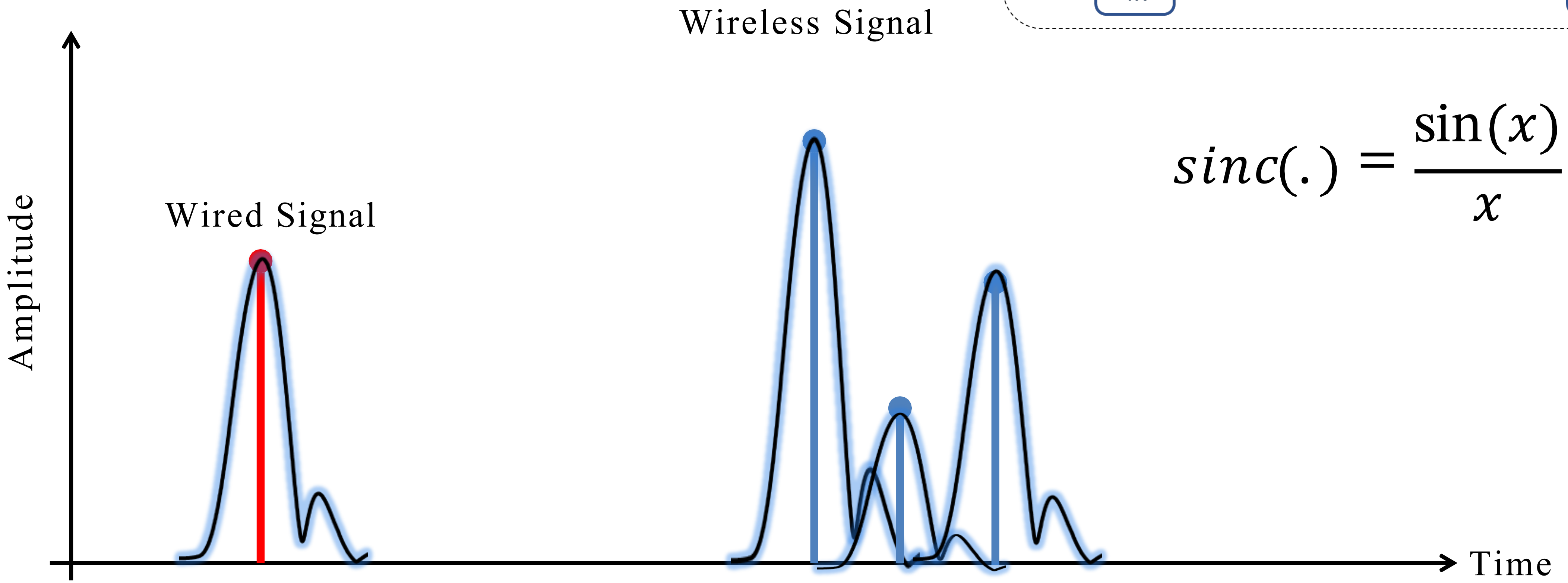




$$sinc(.) = \frac{\sin(x)}{x}$$

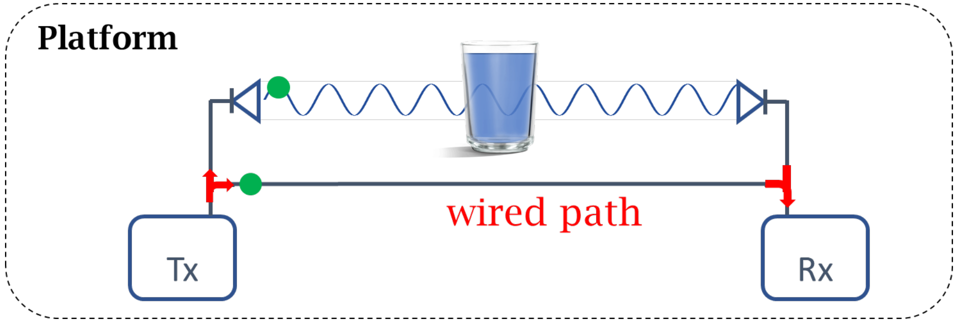
Multipath causes more Distortions

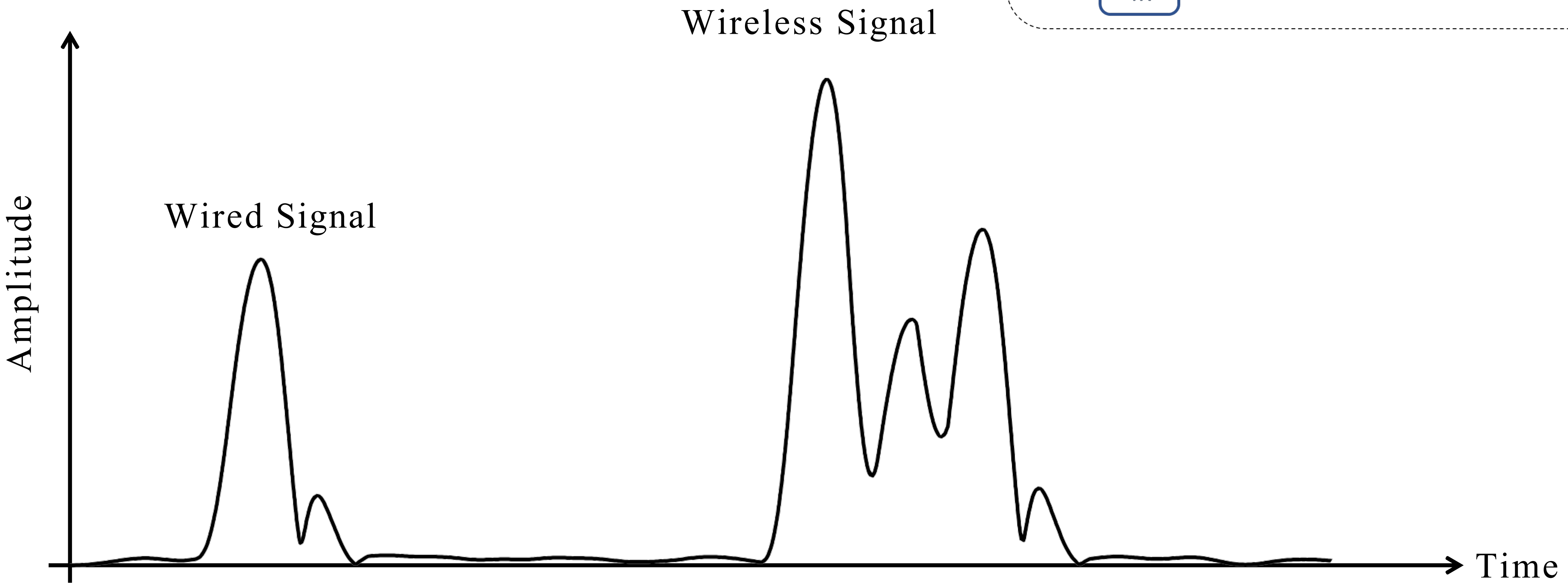




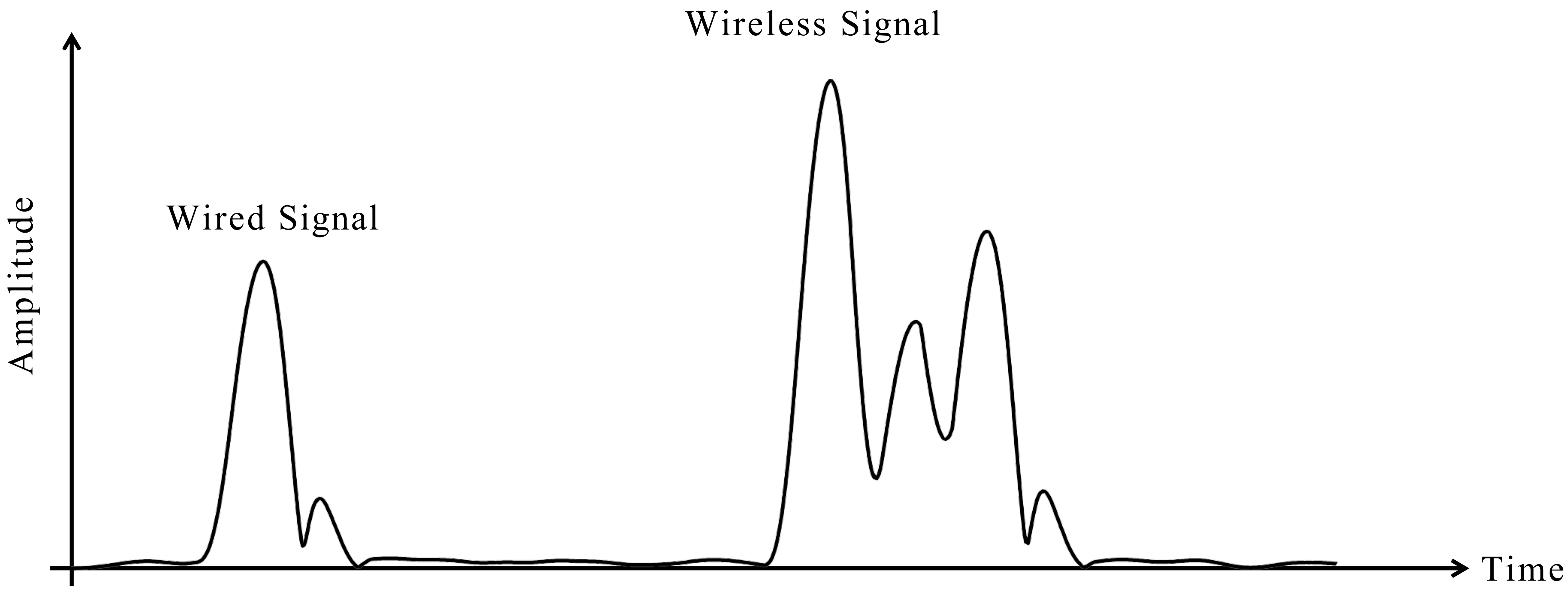
$$sinc(.) = \frac{\sin(x)}{x}$$

This is the received signal at Rx





Main question: Where are the wired, wireless impulses?



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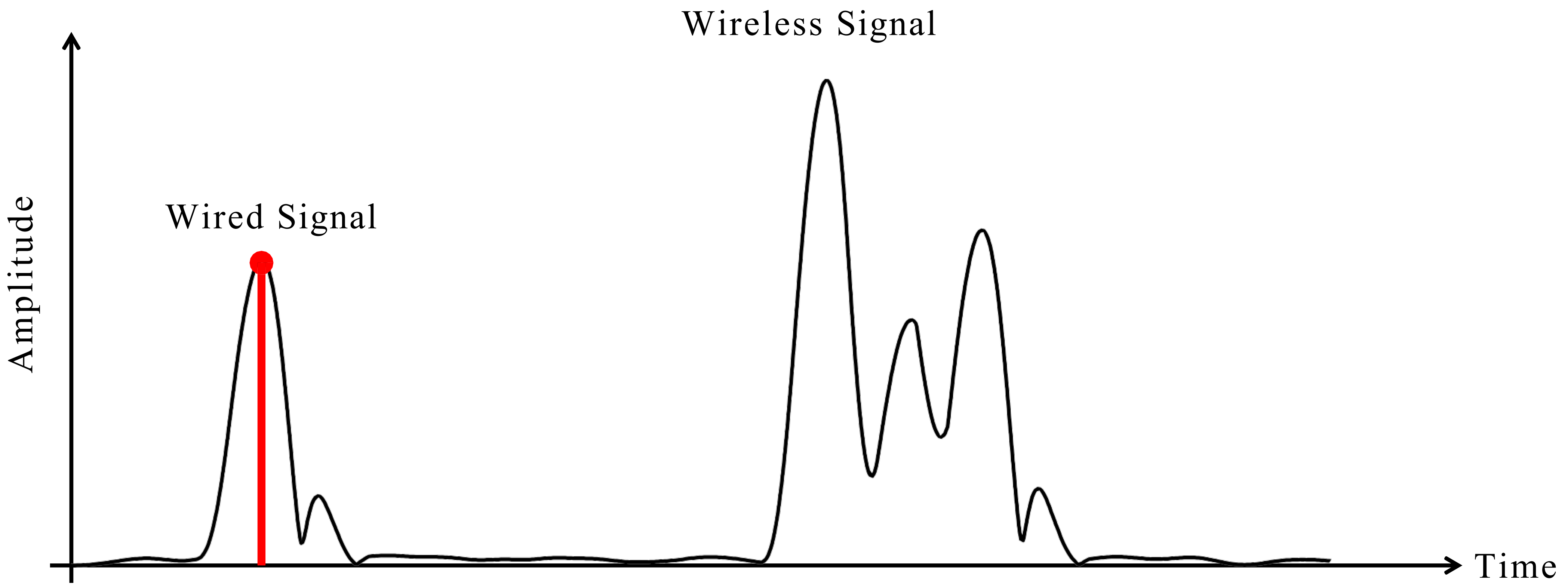

Wired impulse is easy

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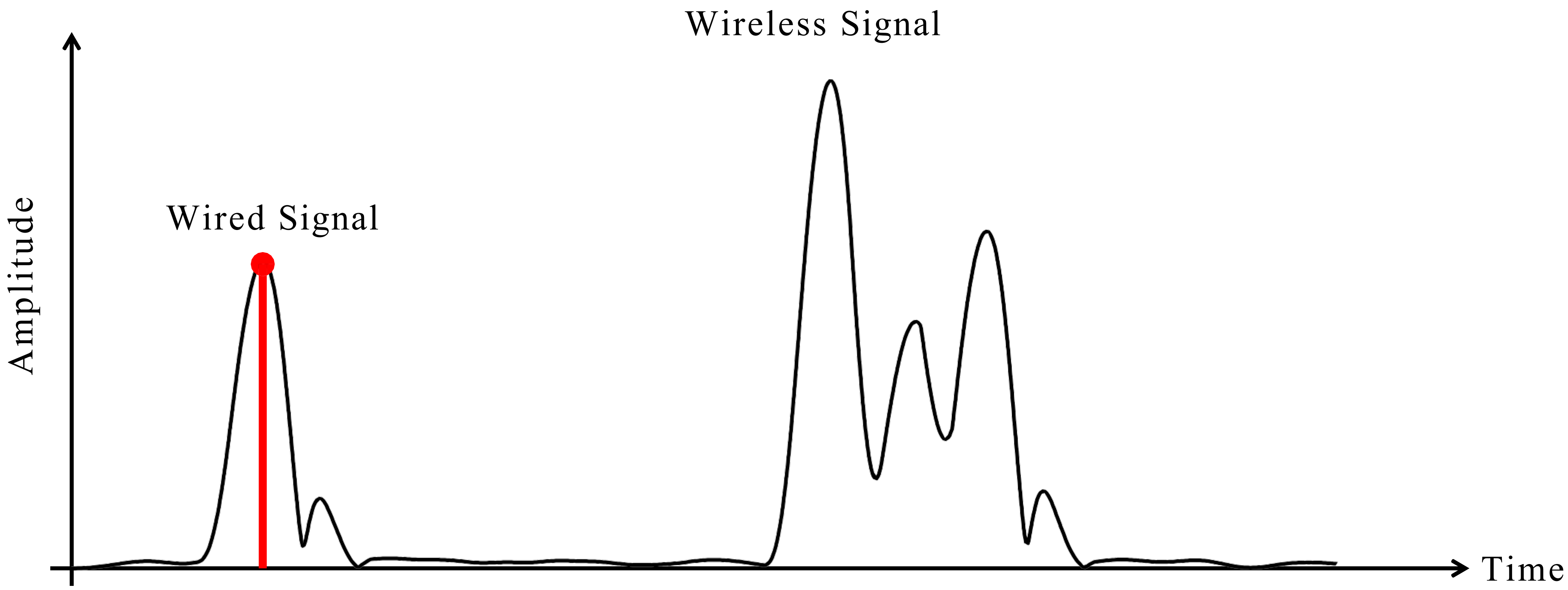

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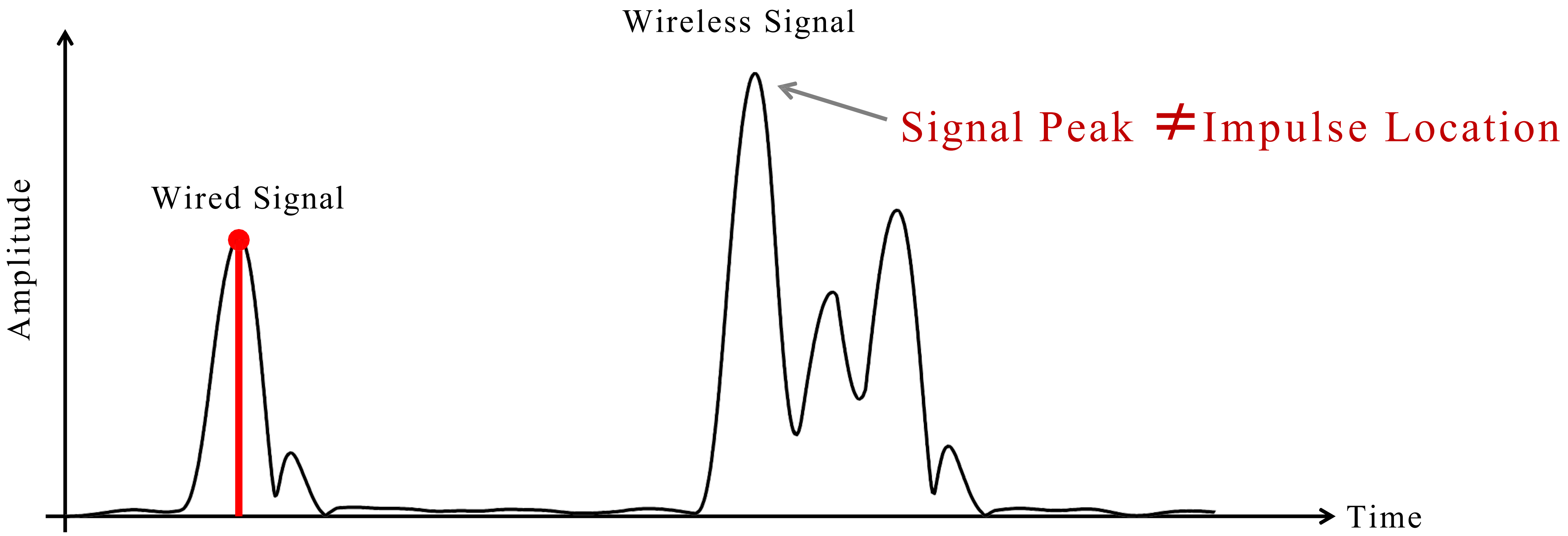

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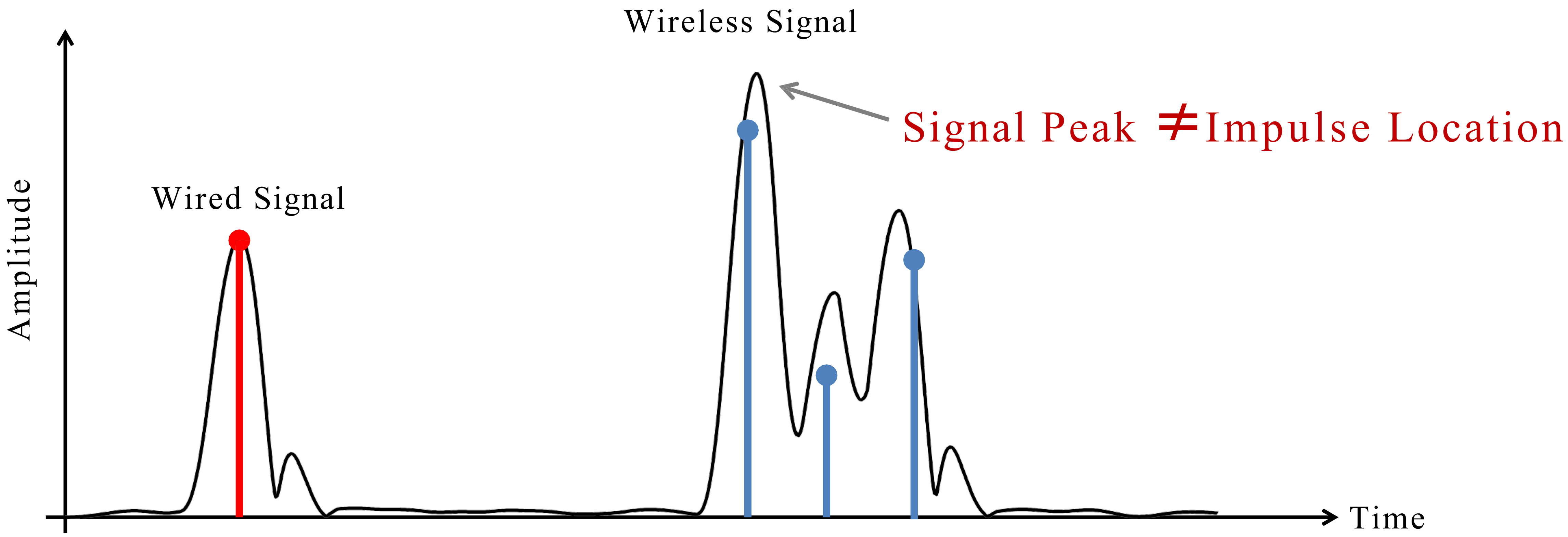

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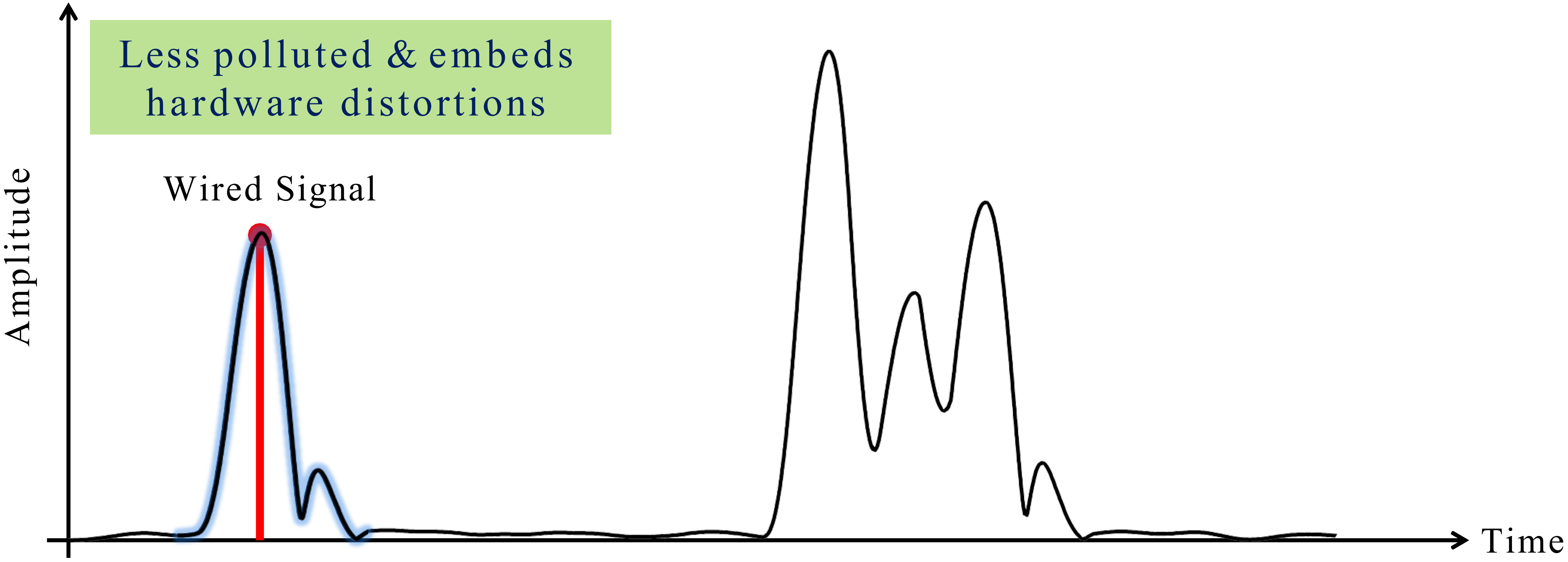
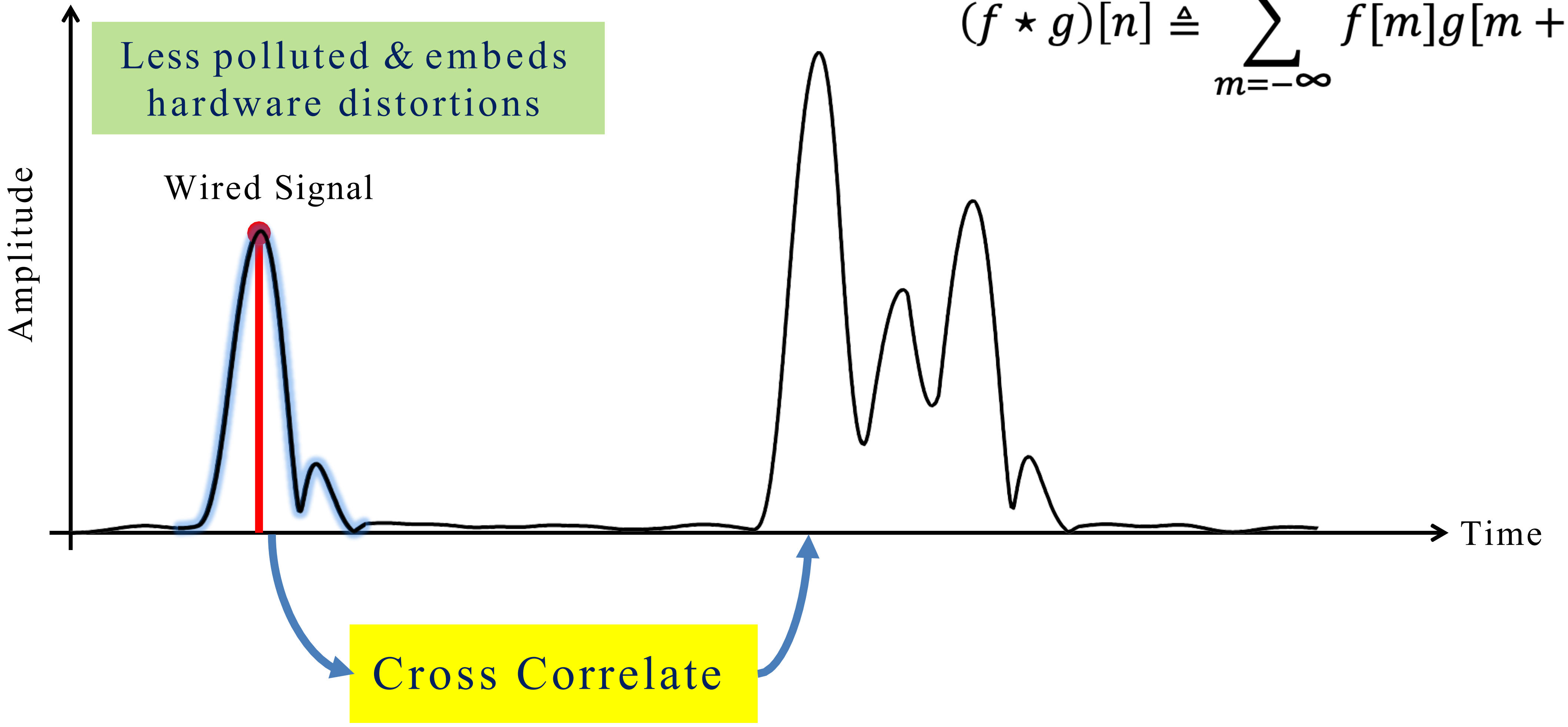
Template Matching



Template Matching

$$(f \star g)[n] \triangleq \sum_{m=-\infty}^{\infty} \overline{f[m]}g[m+n]$$



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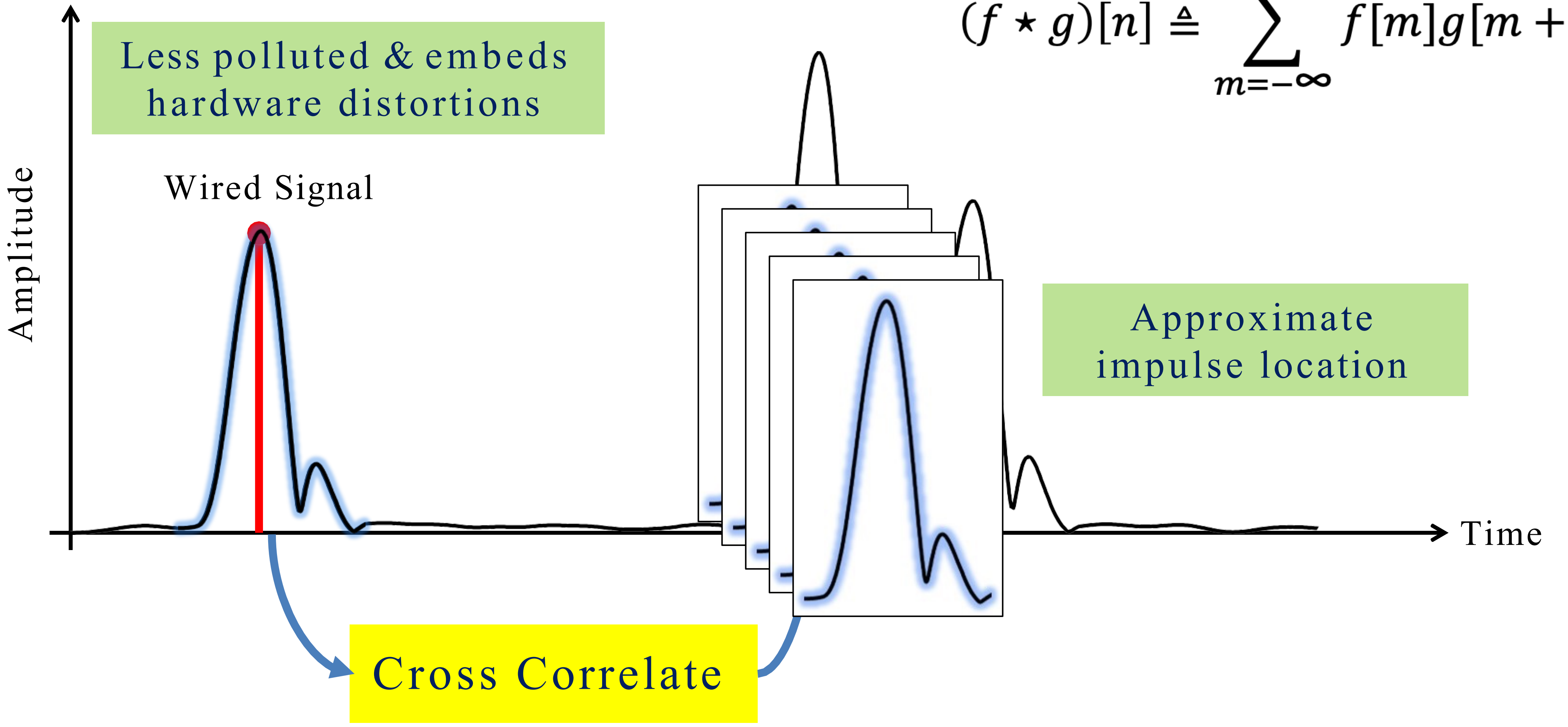
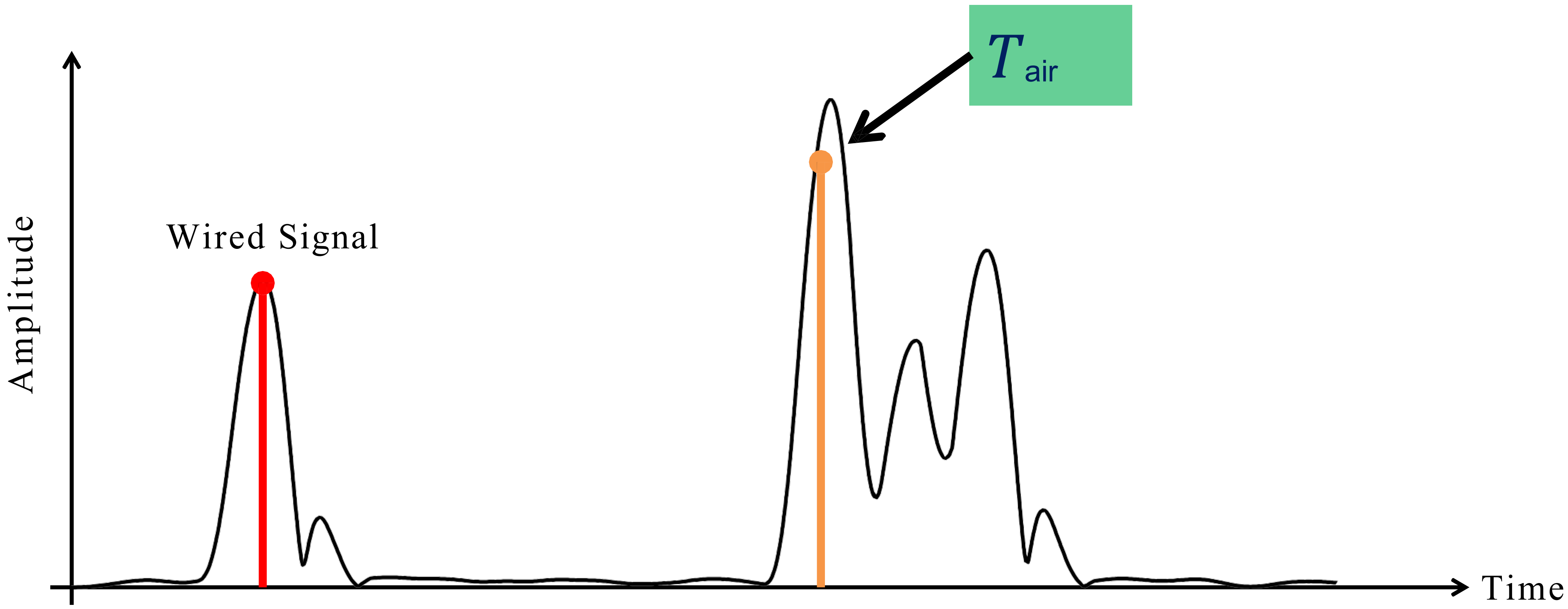
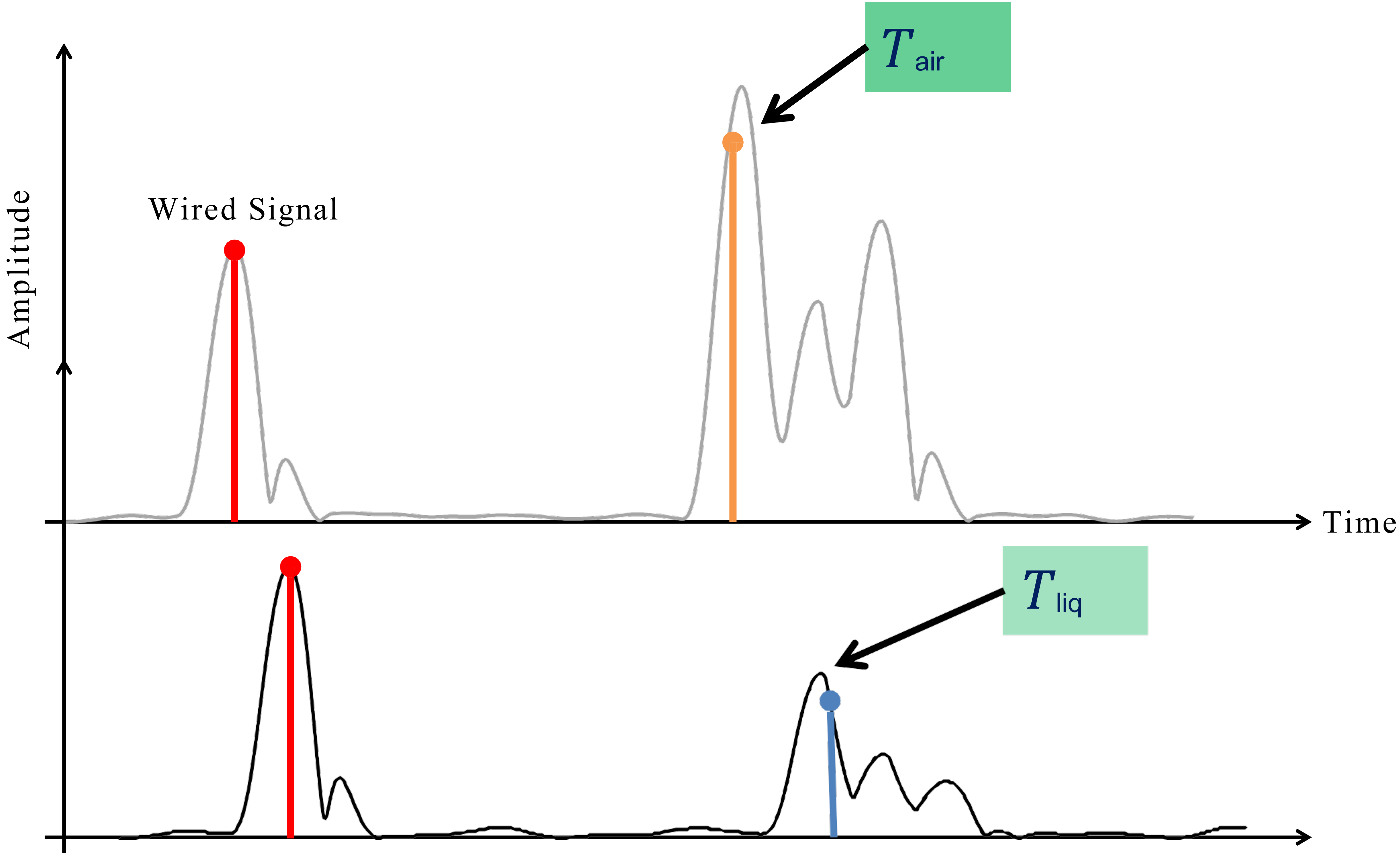
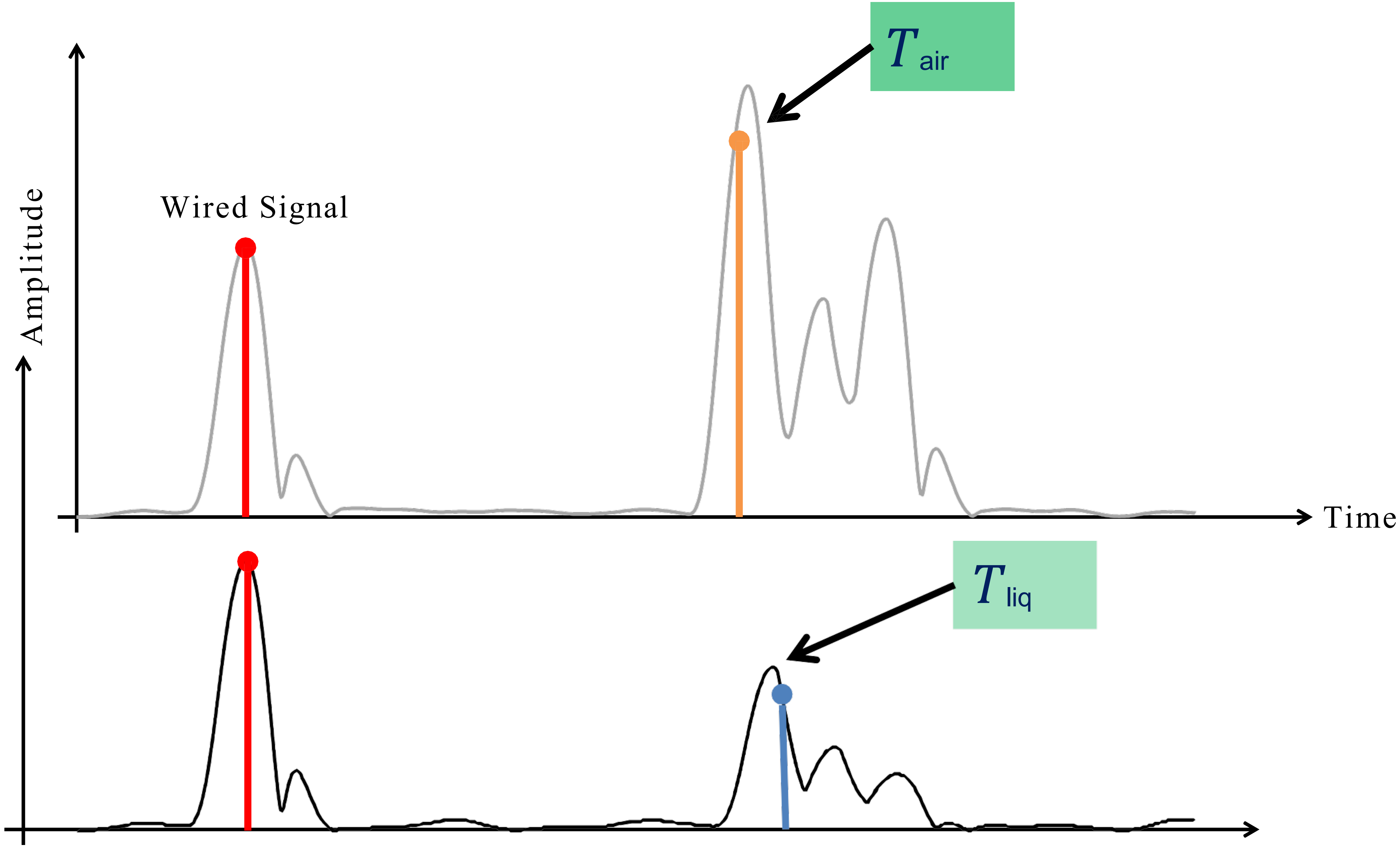


Correct Time Value for Air





Amplitude
Wired Signal
T_{air}
Time
T_{liq}


T_{air}
Wired Signal
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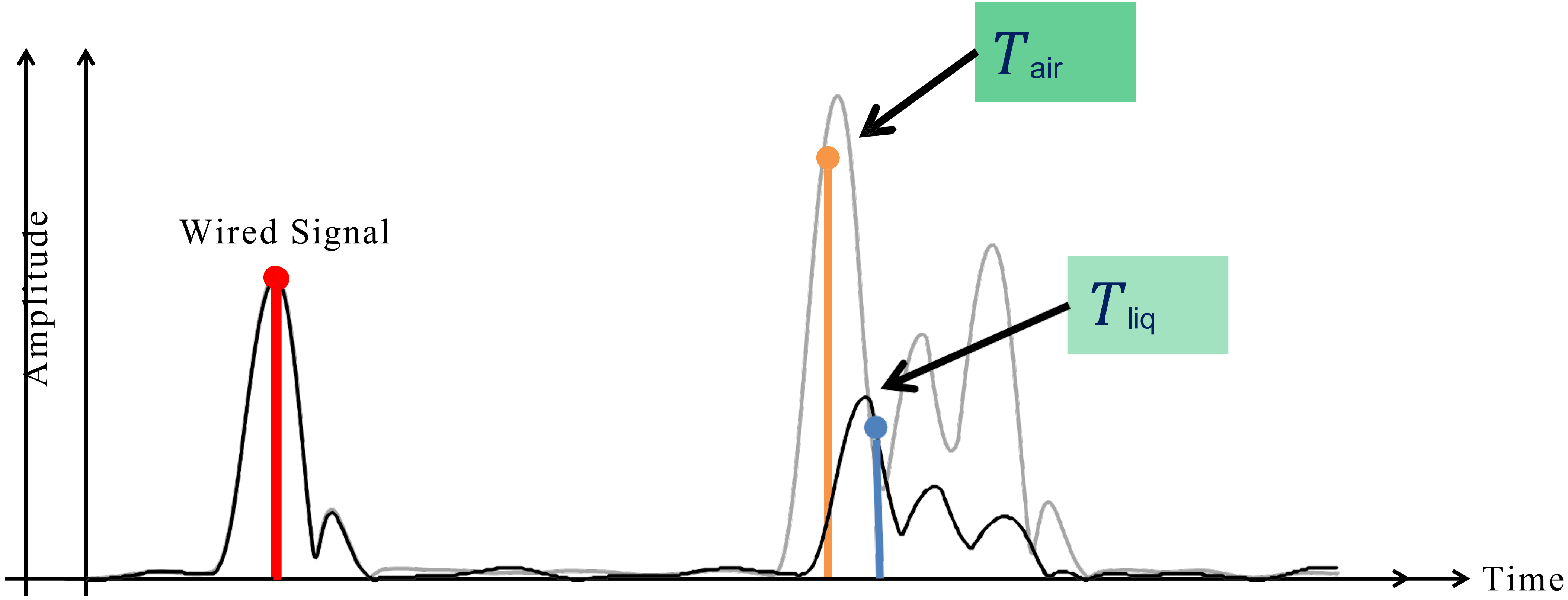
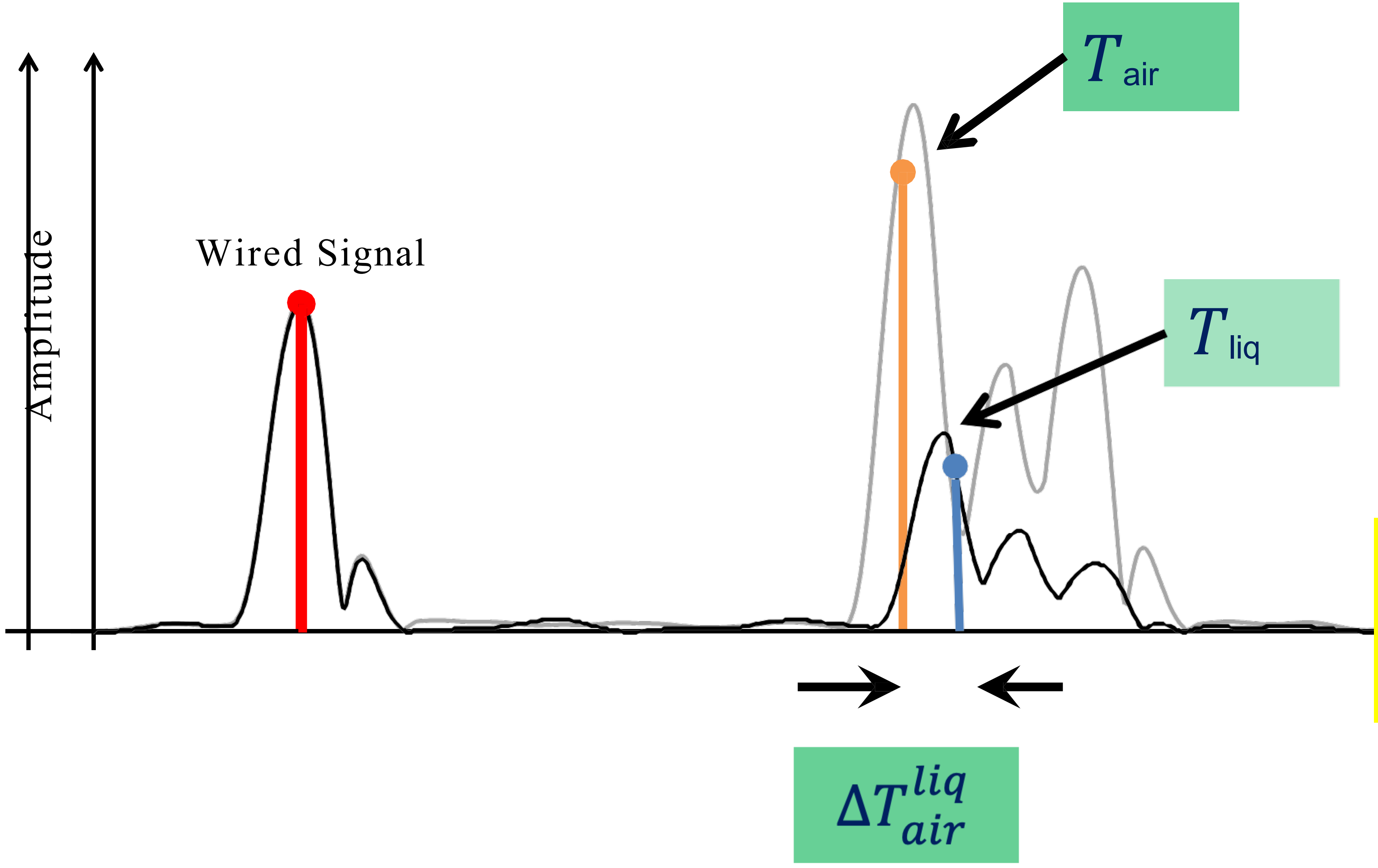


Amplitude
Wired Signal
T_{air}
T_{liq}
Time

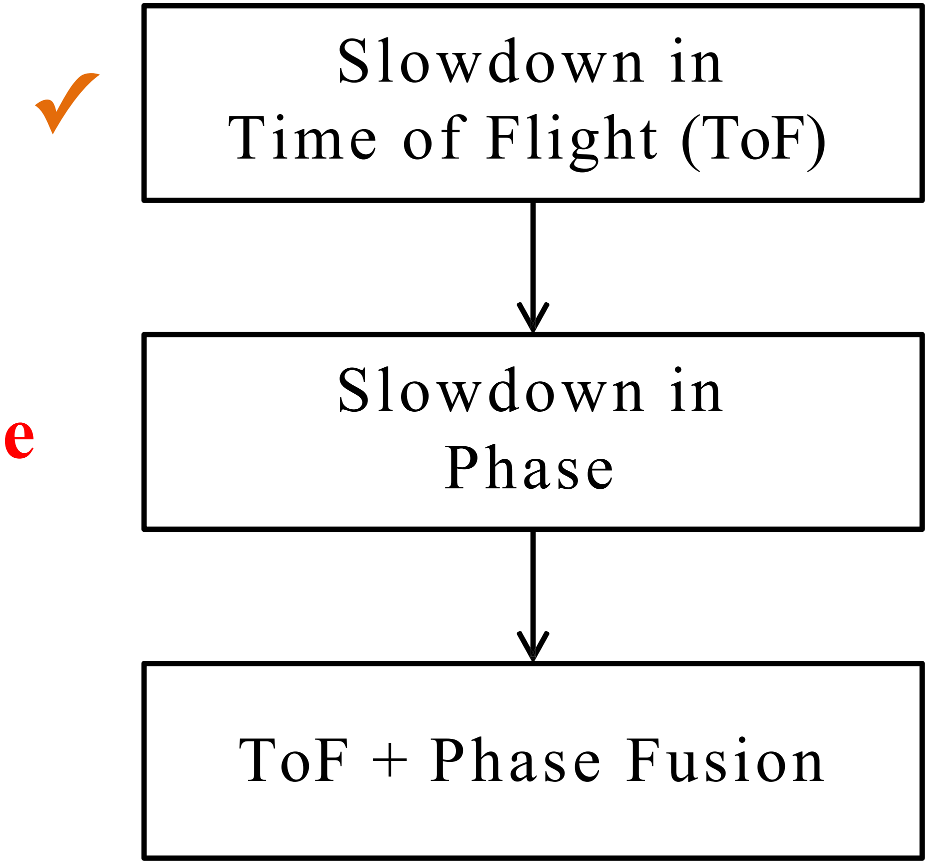


Gives the slowdown in time

$$\Delta T_{air}^{liq} = (T_{liq} - T_{wire}) - (T_{air} - T_{wire})$$

✓ Slowdown in
Time of Flight (ToF)

We now need slowdown in phase



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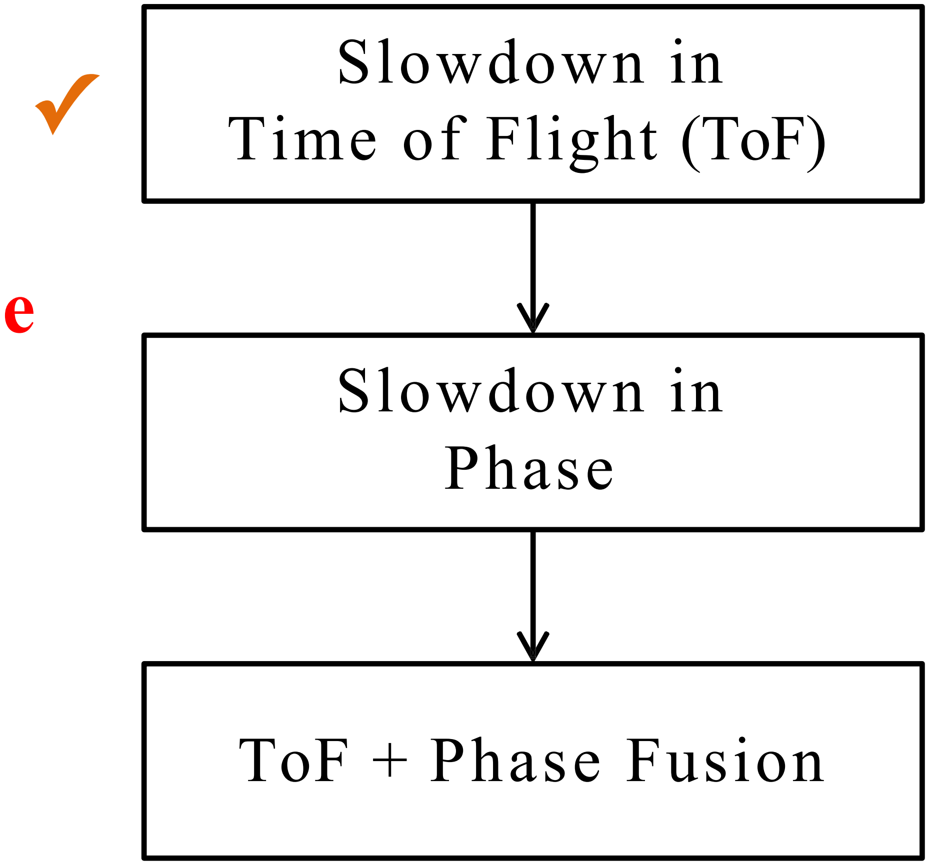
Key Opportunity:
Phase is stable and undistorted



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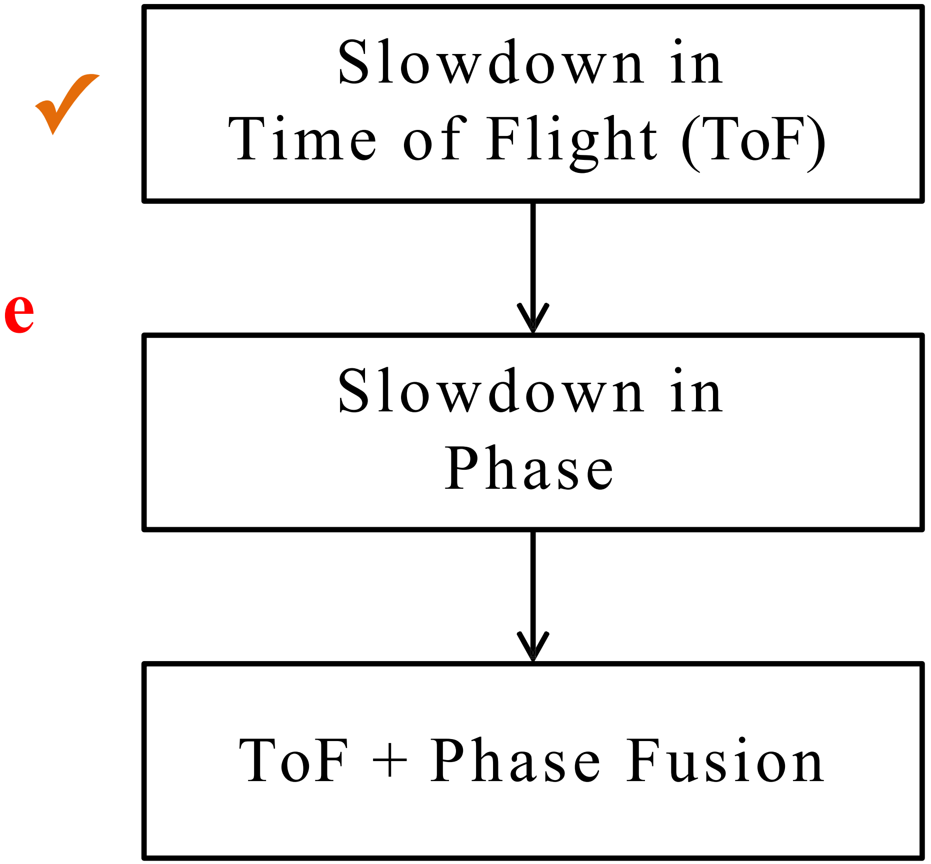
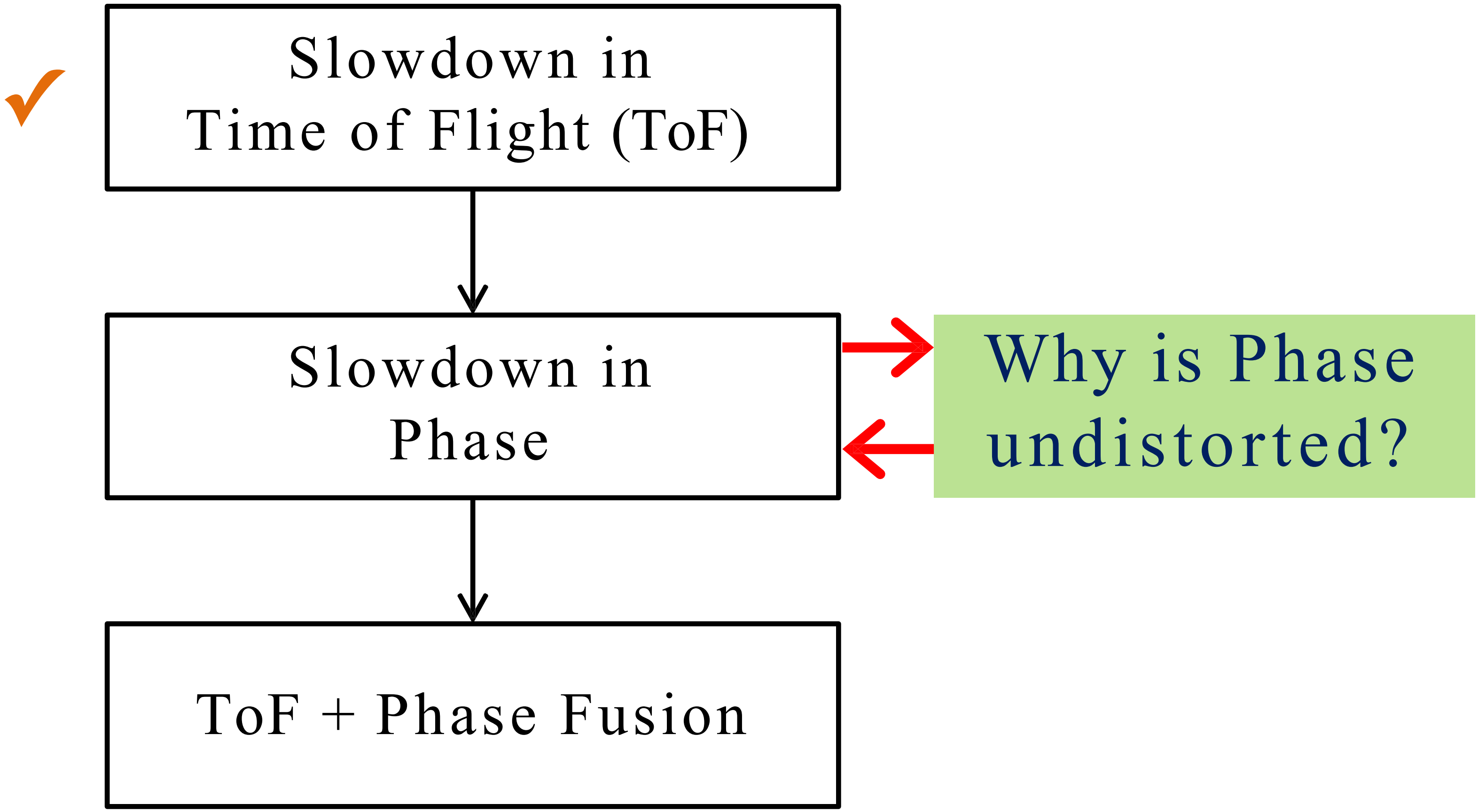
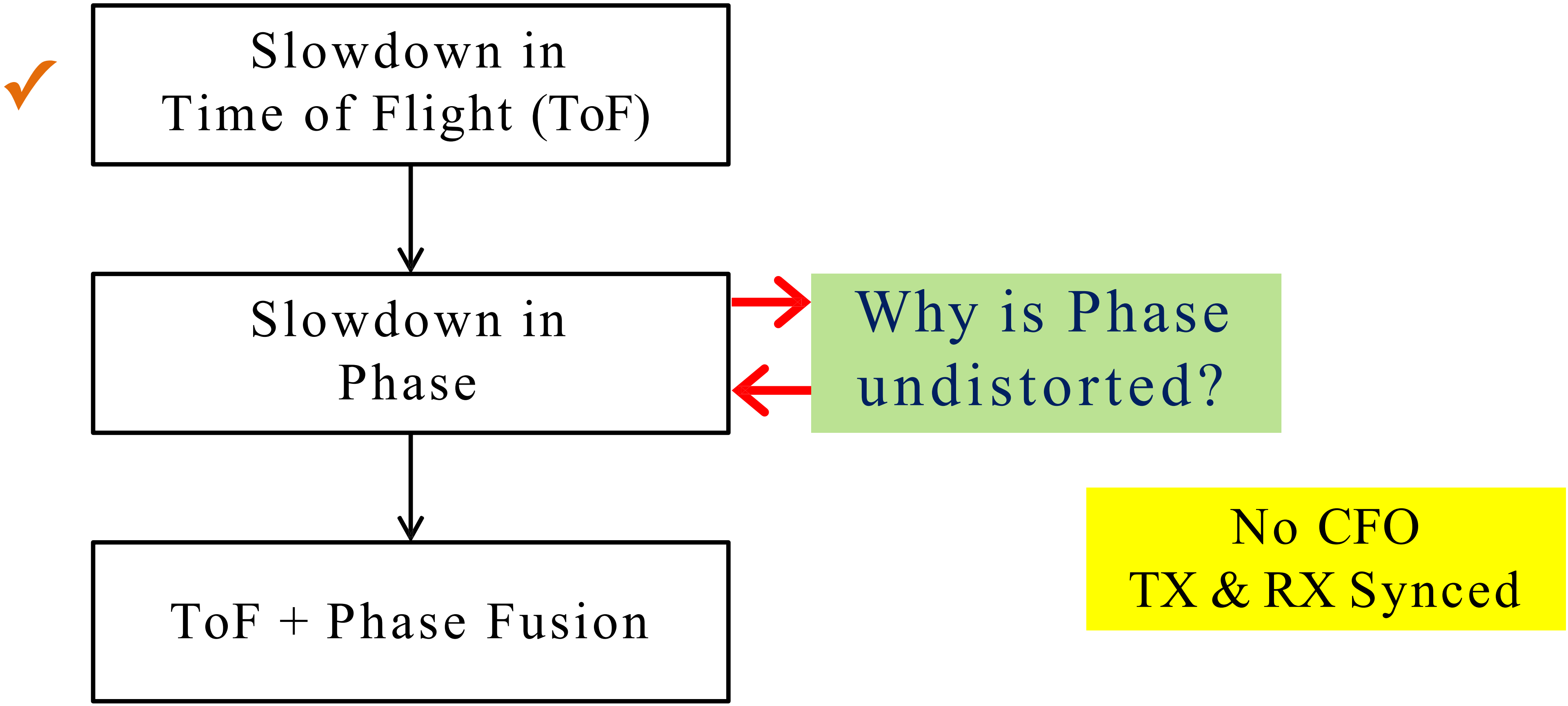
Why?



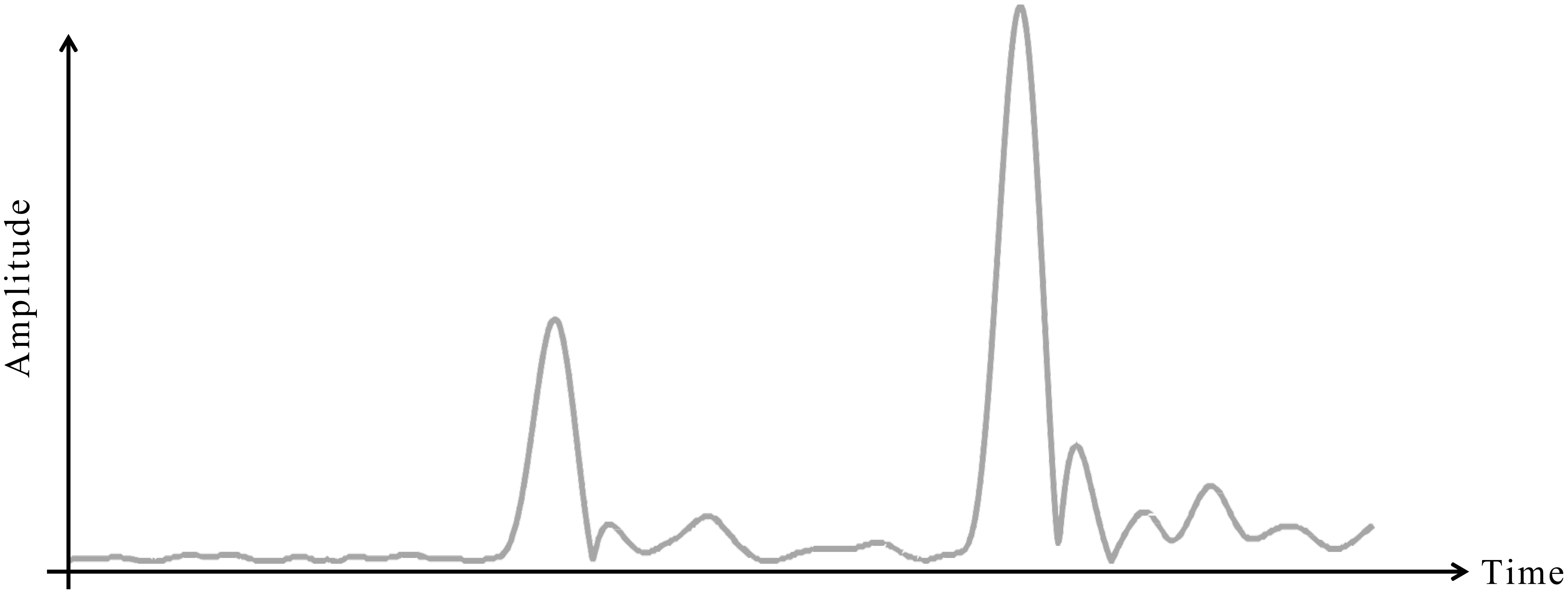
Why?


✓
Slowdown in Time of Flight (ToF)
Slowdown in Phase
Why is Phase undistorted?
ToF + Phase Fusion

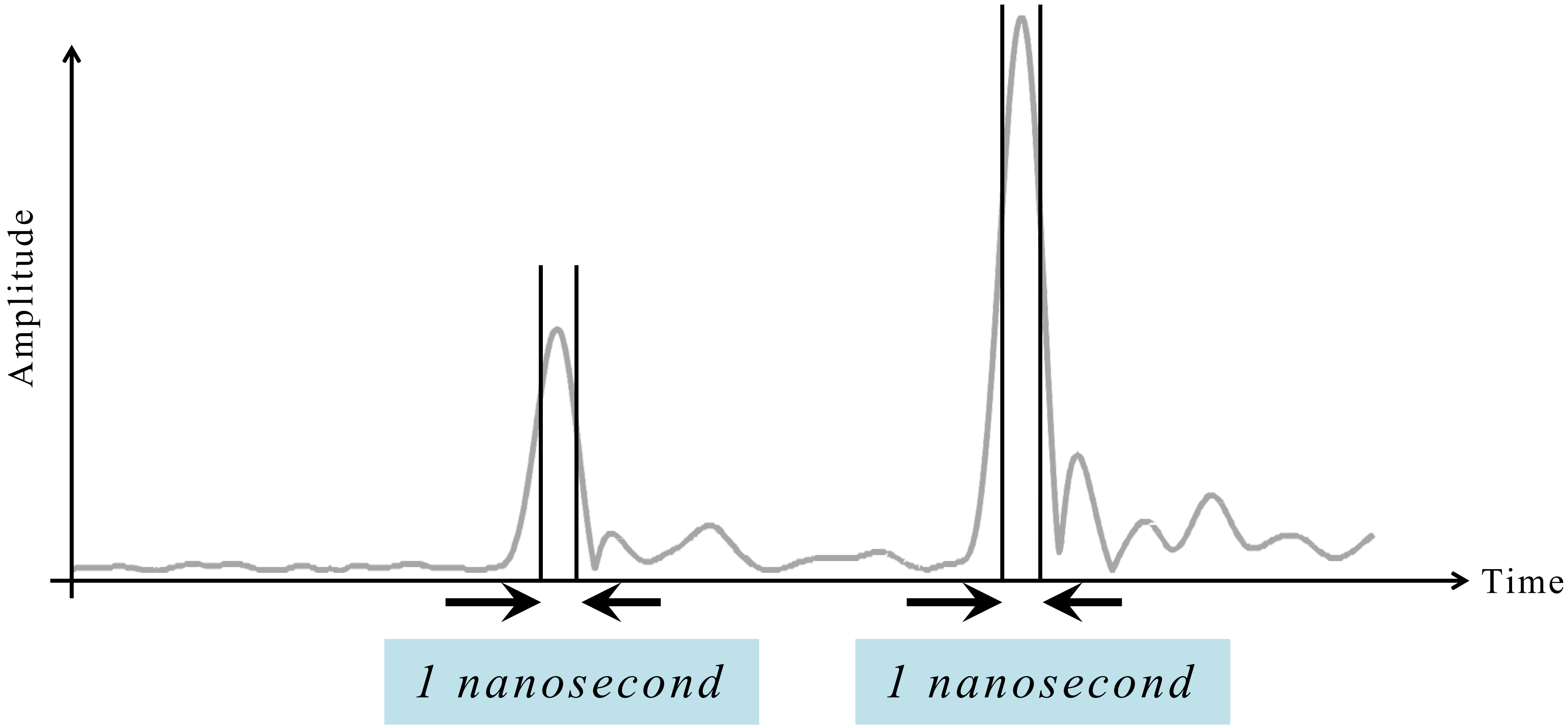
Why?


Slowdown in Time of Flight (ToF)
Slowdown in Phase
ToF + Phase Fusion
Why is Phase undistorted?
No CFO
TX & RX Synced

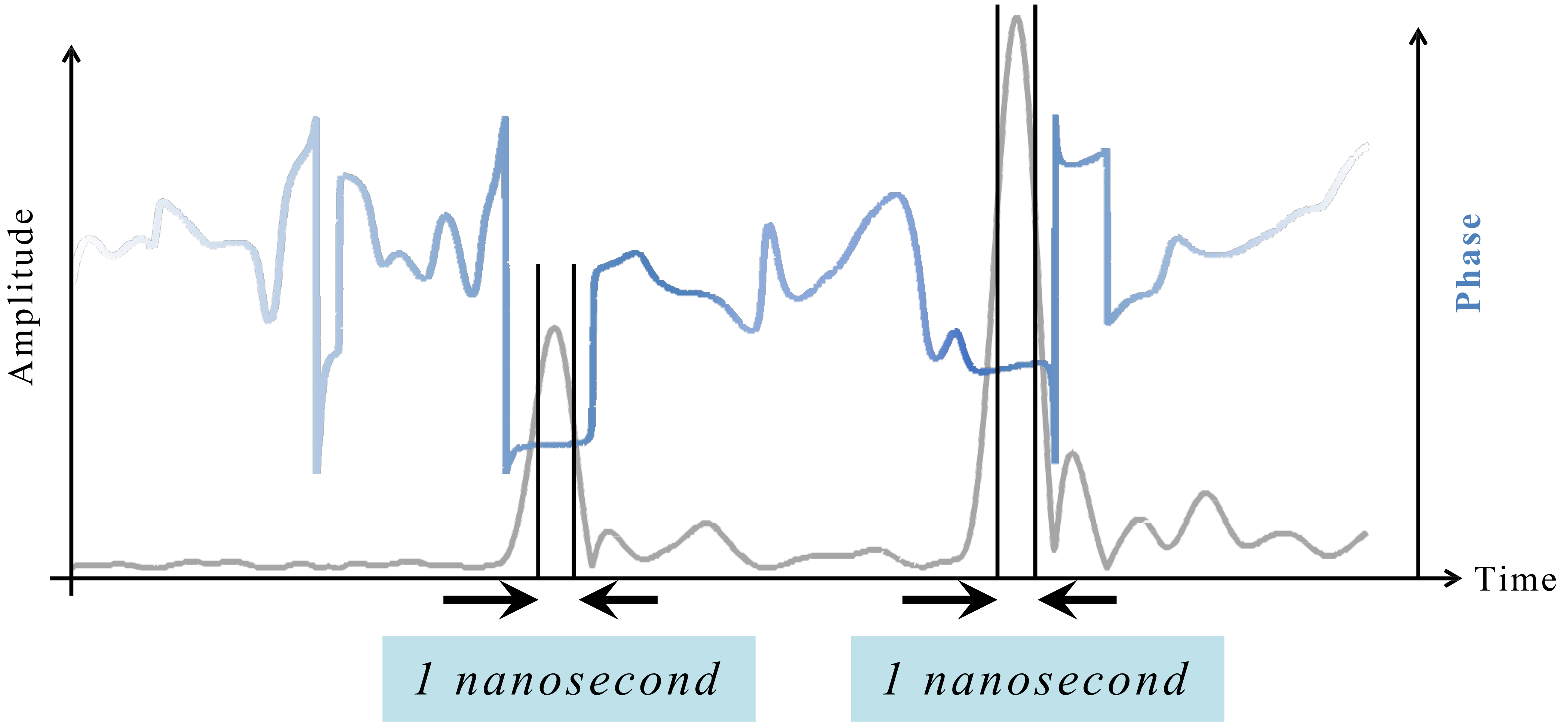
Phase to the Rescue



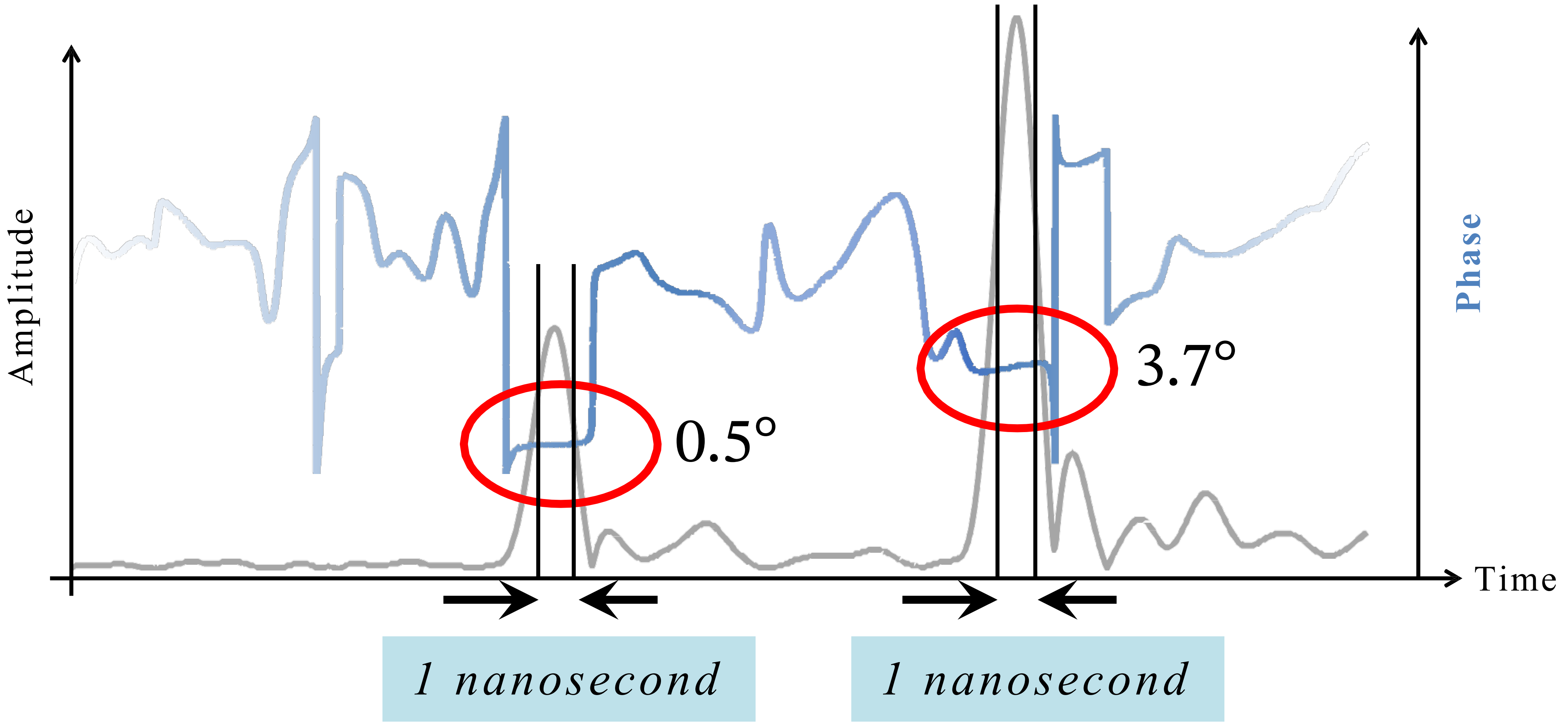
Phase to the Rescue



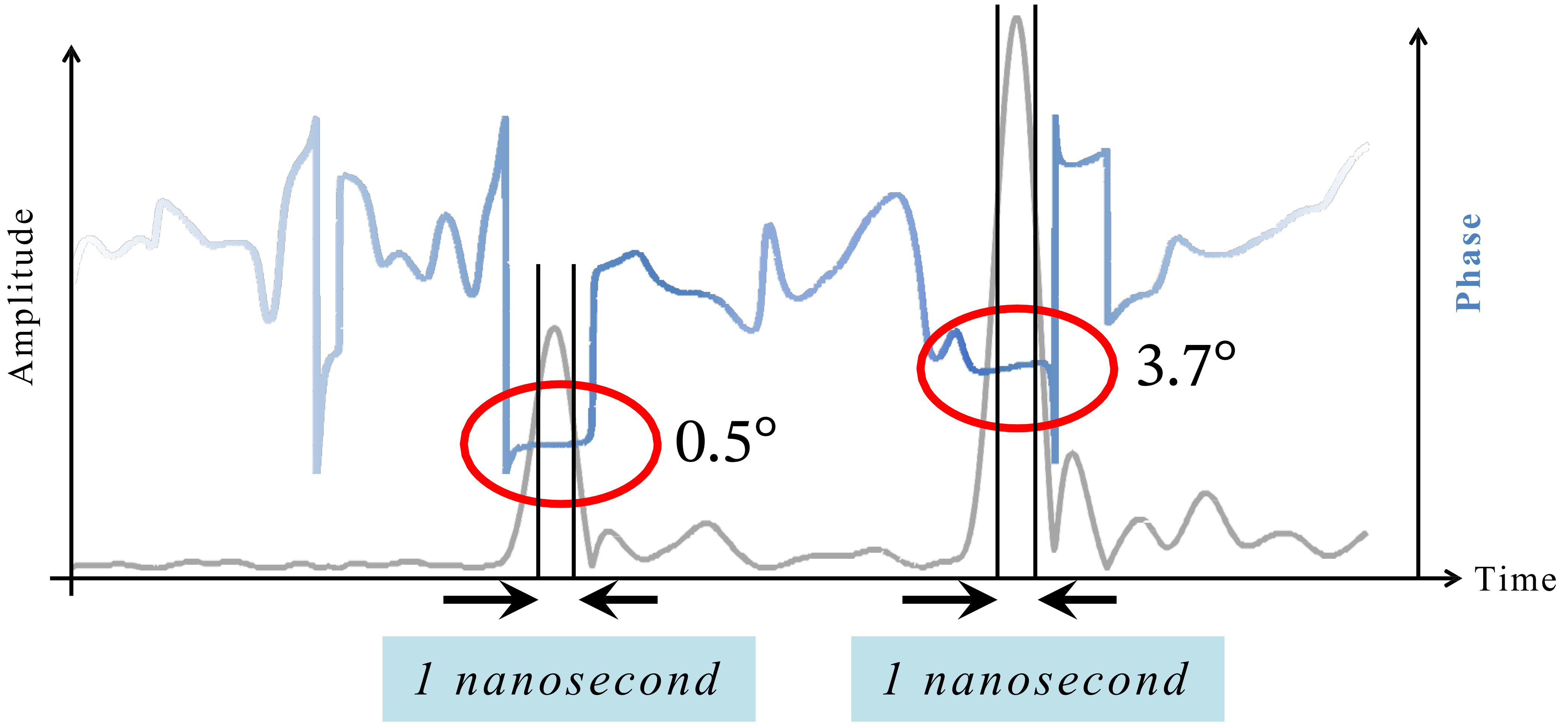
Phase to the Rescue



Phase to the Rescue

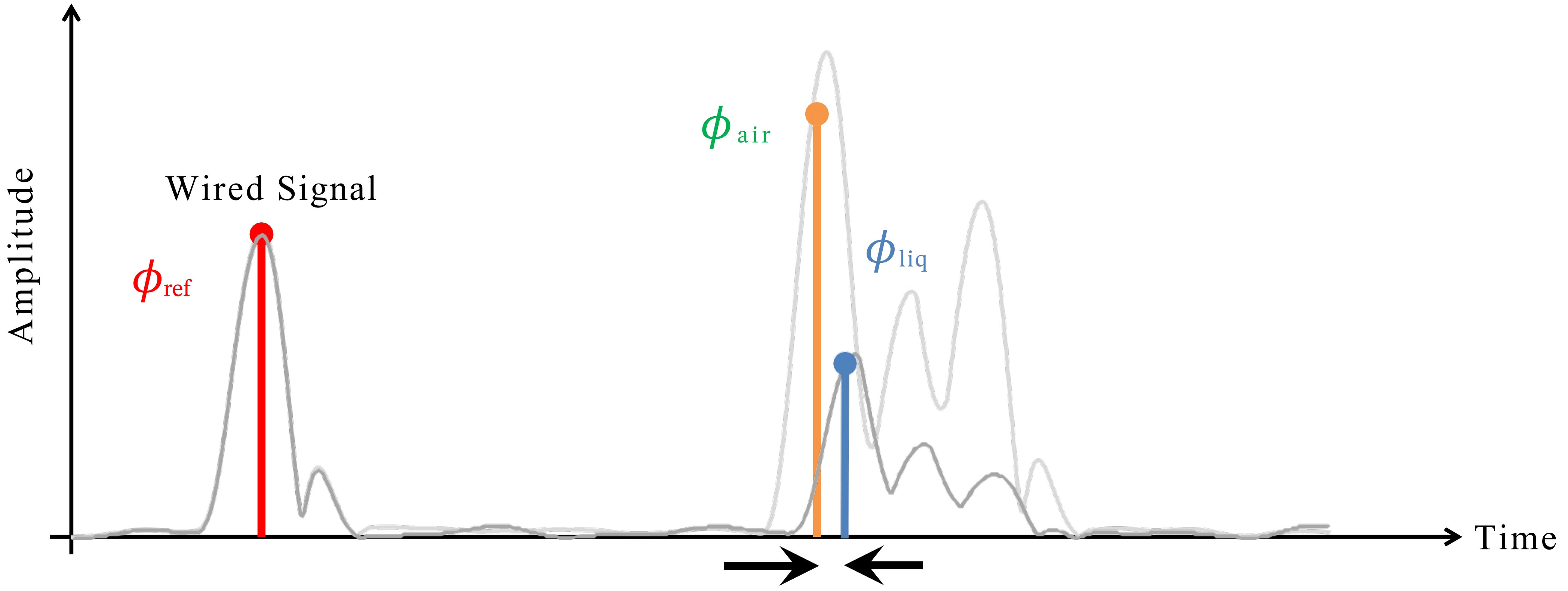


Phase to the Rescue



Phase is undistorted and stable

Double Differencing – Phase



$$\Delta\phi_{air}^{liq}$$

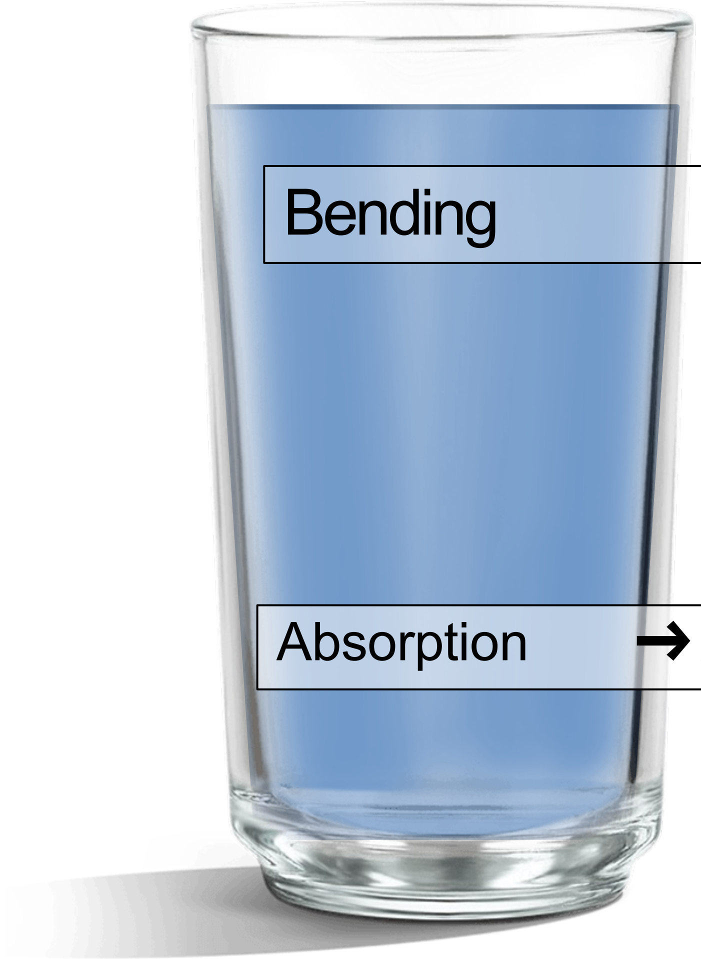
$$\Delta\phi_{air}^{liq} = (\phi_{liq} - \phi_{ref}) - (\phi_{air} - \phi_{ref})$$

Fuse time + phase → Refractive index

ΔT_{air}^{liq} in nanoseconds

$\Delta \phi_{air}^{liq}$ in picoseconds

Key Properties of Liquid

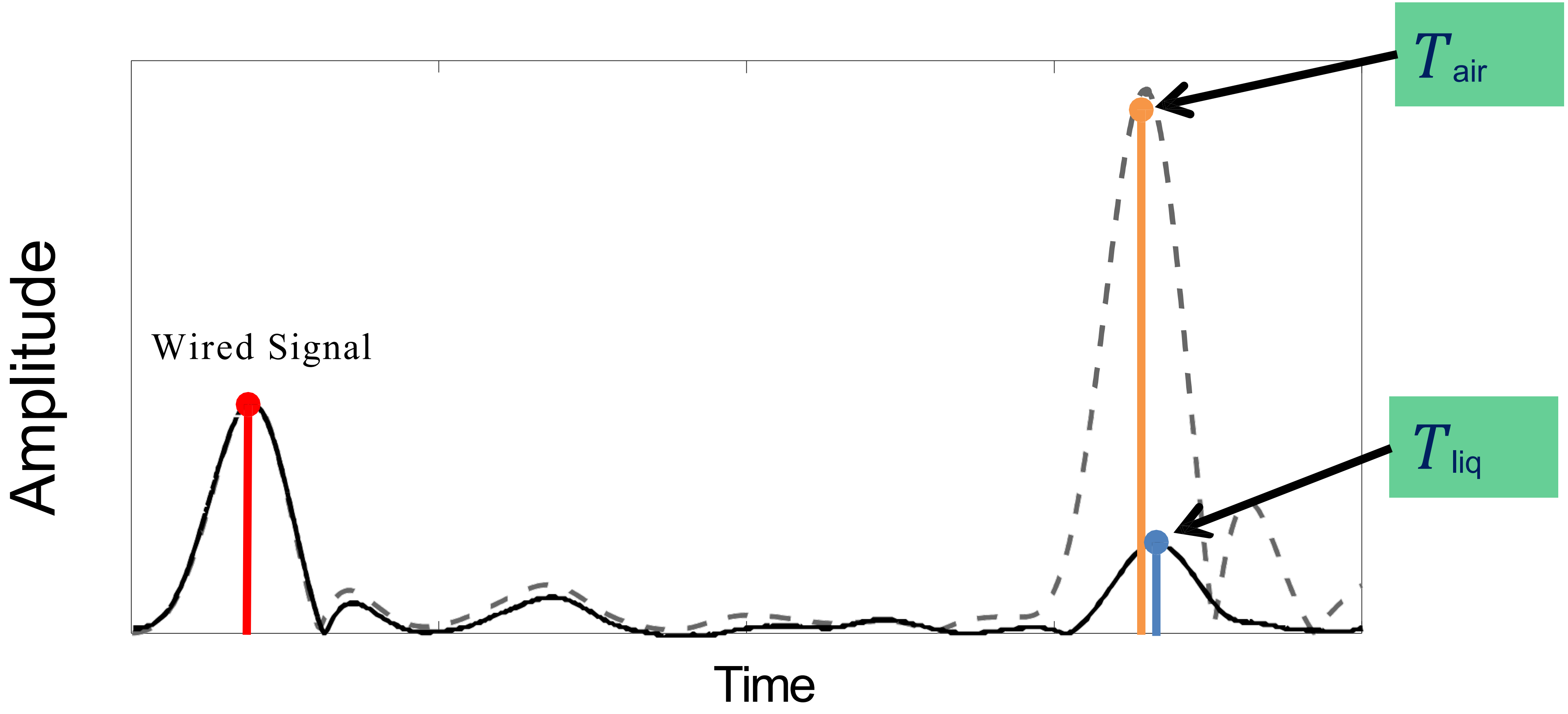


Bending → Refractive Index ✓

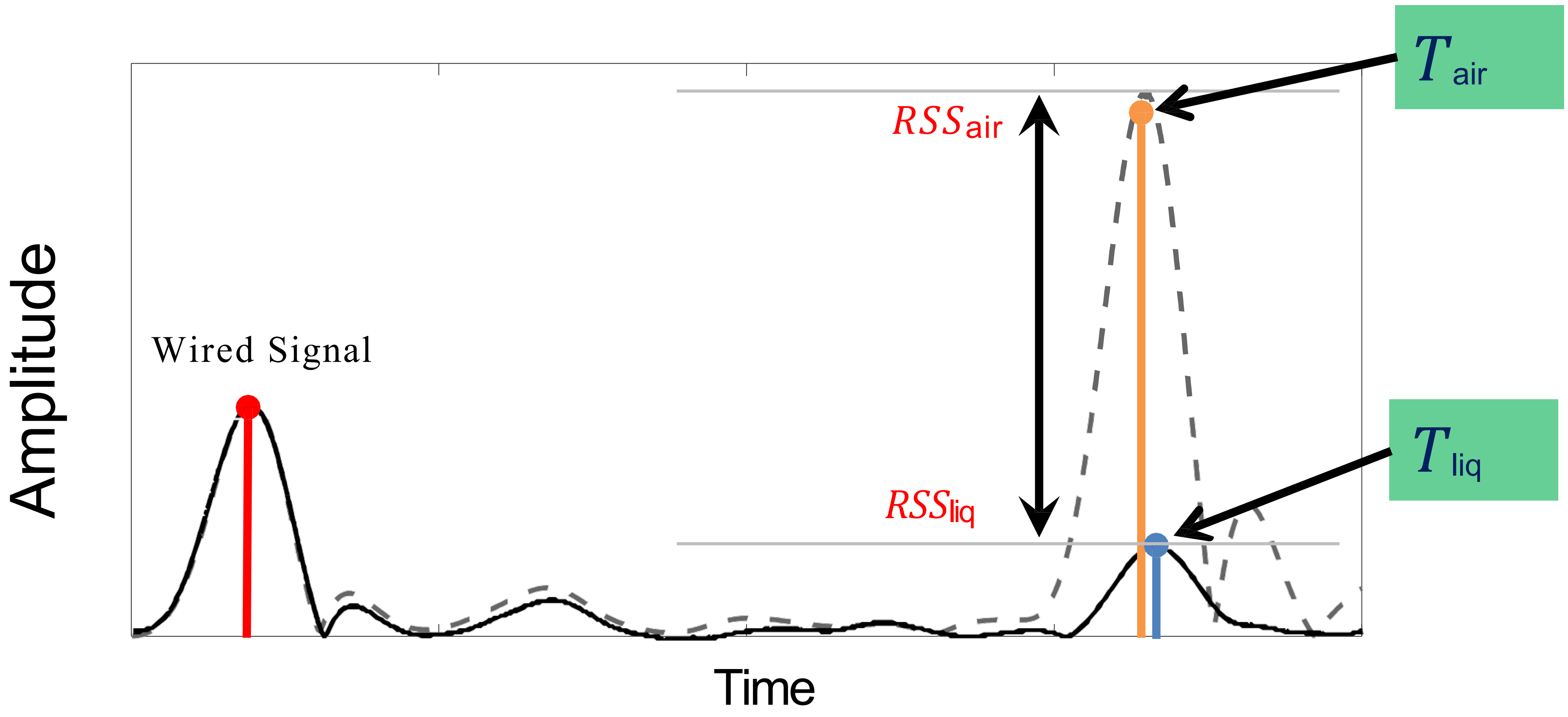
Absorption → Attenuation Factor

Unique Tuple

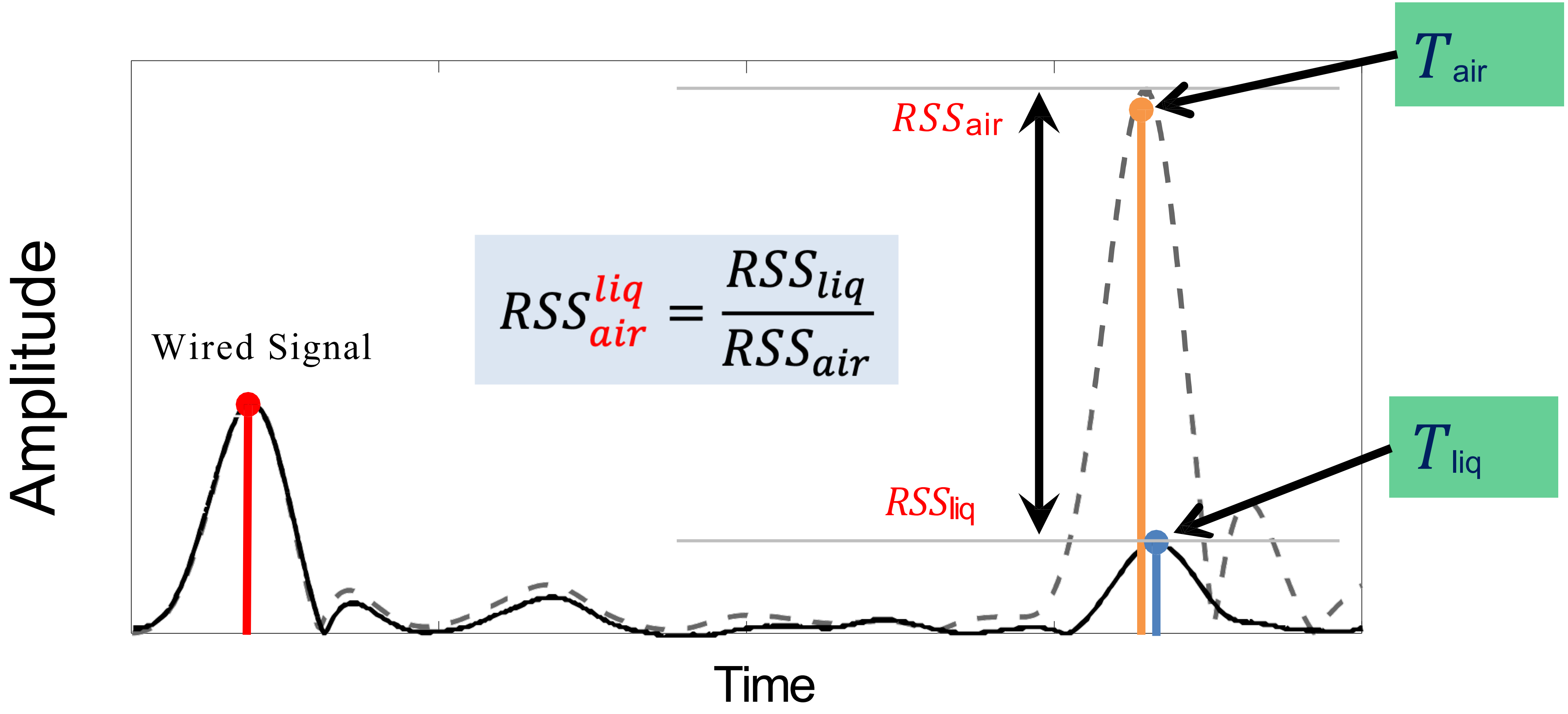
Estimating Attenuation



Estimating Attenuation



Estimating Attenuation



Obtaining Complex Permittivity

$$Complex\ Permittivity = \epsilon' + j\epsilon''$$

$$Complex\ Permittivity = f(Refractive\ Index, Attenuation\ Factor)$$

Obtaining Complex Permittivity

$$Complex\ Permittivity = \epsilon' + j\epsilon''$$

$$Refractive\ Index = \sqrt{\frac{1}{2}\epsilon'\left\{\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2}+1\right\}}$$

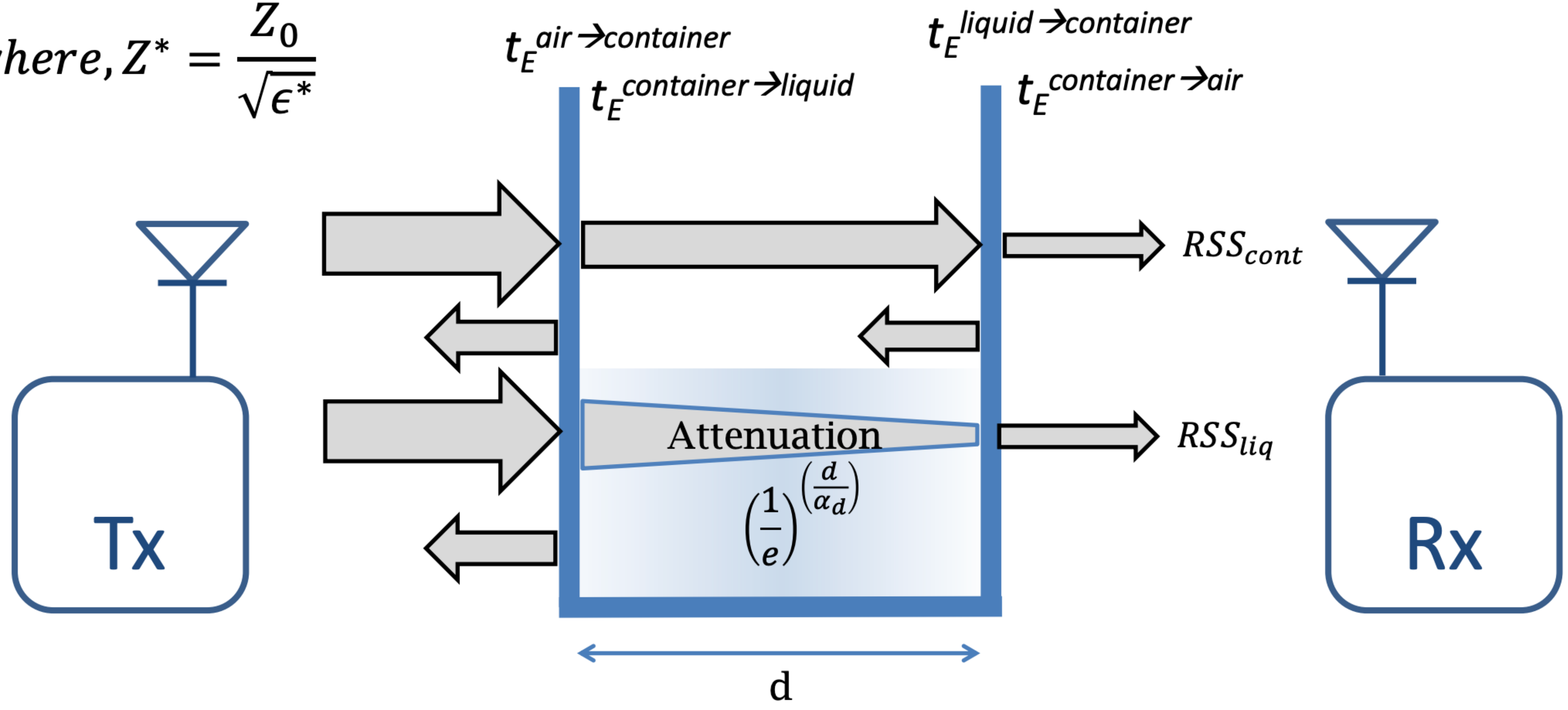
$$Attenuation\ Factor = \frac{\lambda_0}{2\pi}\sqrt{\frac{2}{\epsilon'\left(\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2}-1\right)}}$$

Solve for ϵ' and ϵ''

Container Compensation

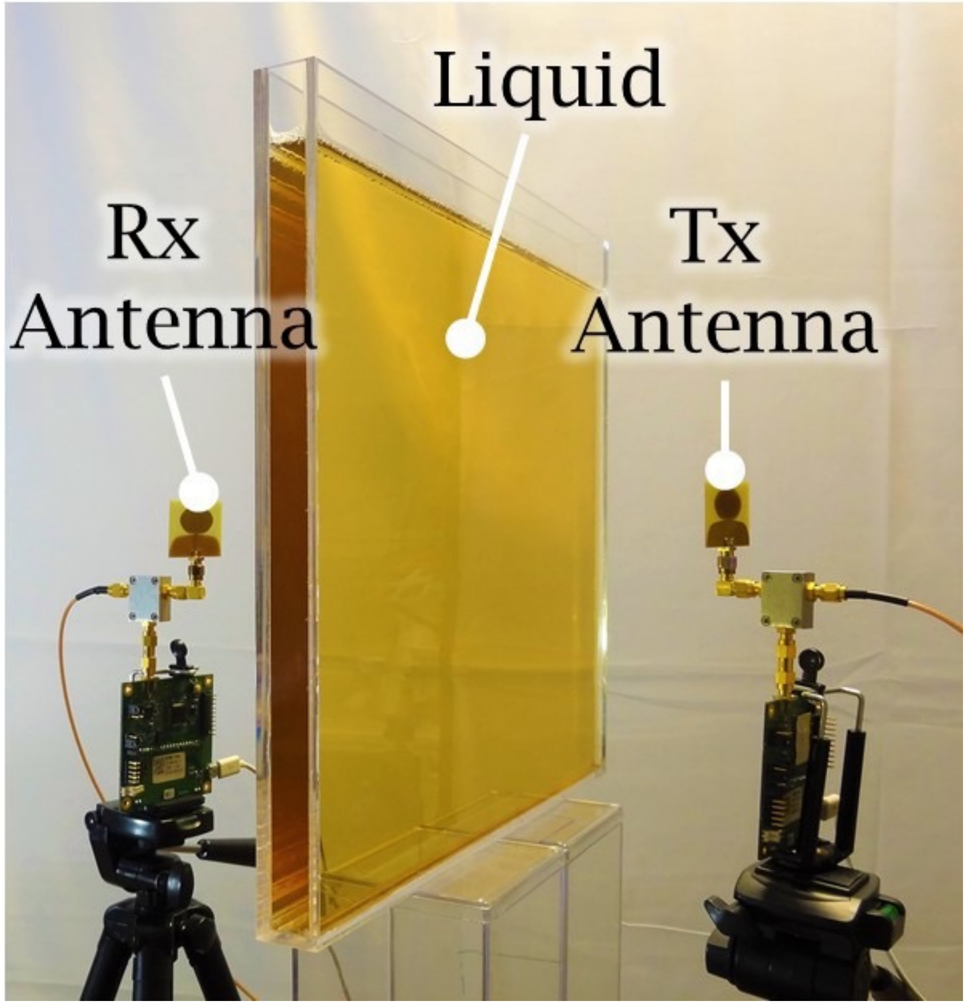
$$t_E = \frac{2Z_2}{Z_2 + Z_1}$$

$$where, Z^* = \frac{Z_0}{\sqrt{\epsilon^*}}$$

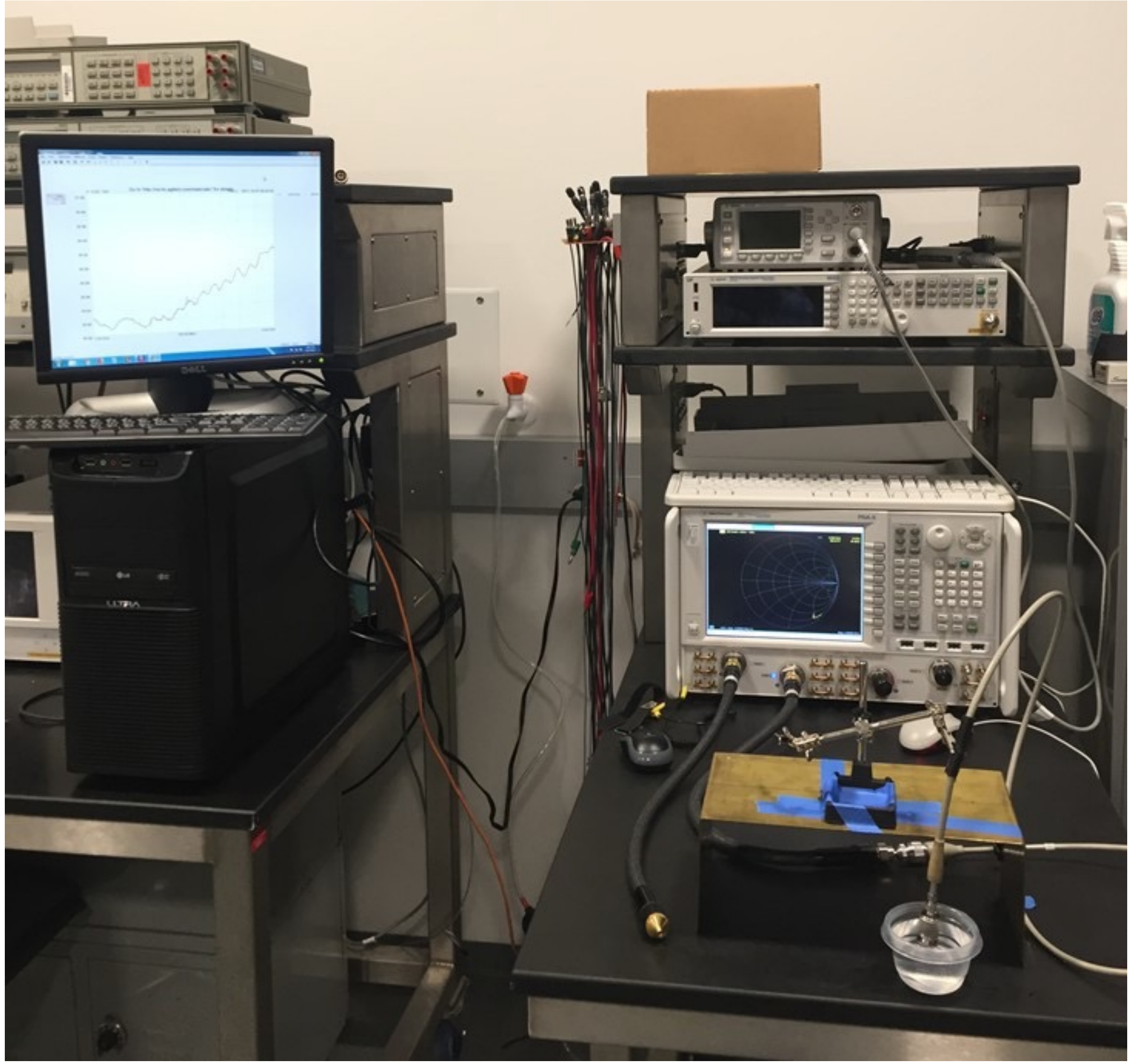


Experimental Setup

- Used Decawave Trek 1000 UWB devices at 4GHz
- 38cm x 36cm liquid container
- 33 liquids spanning a large part of the refractive index spectrum



Baseline: Vector Network Analyzer

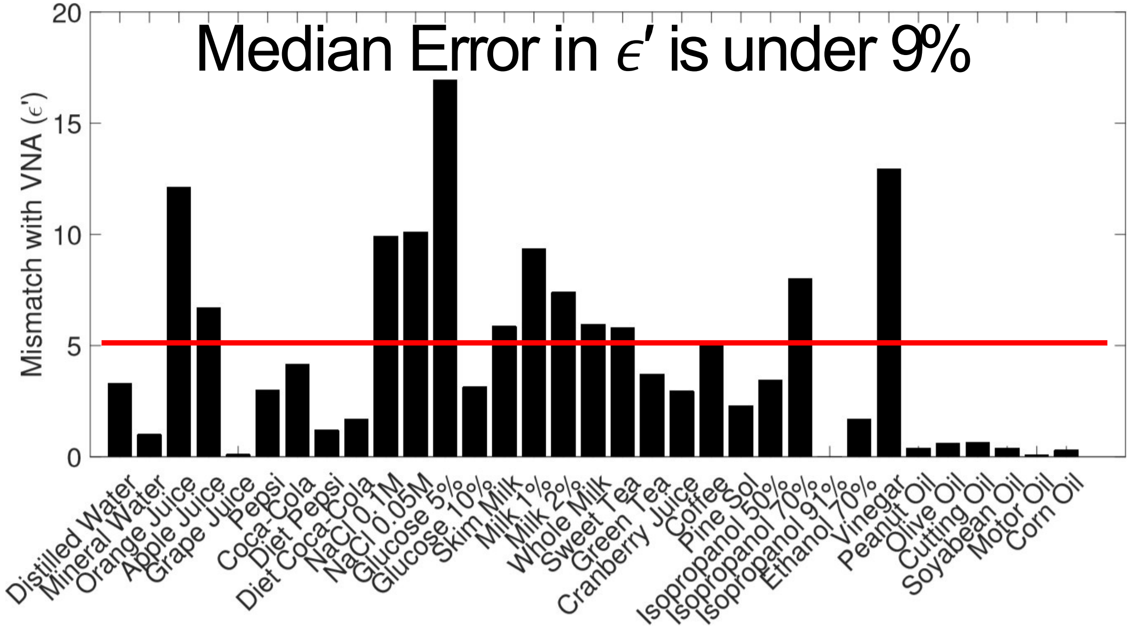


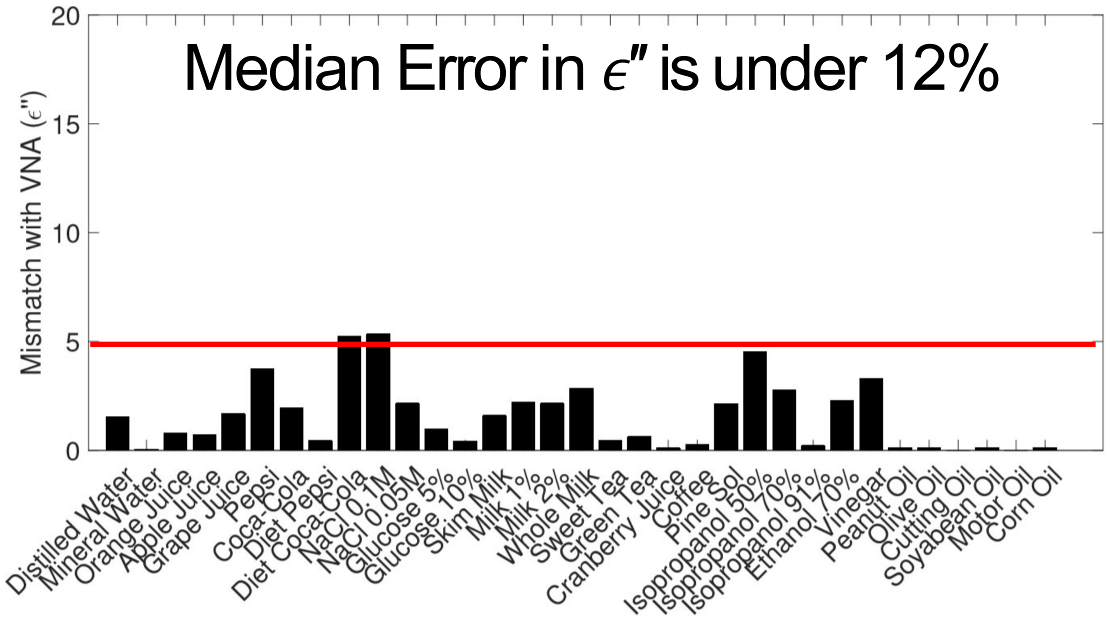
- VNA + Dielectric Probe method for creating a baseline

- Measures the liquid's complex permittivity

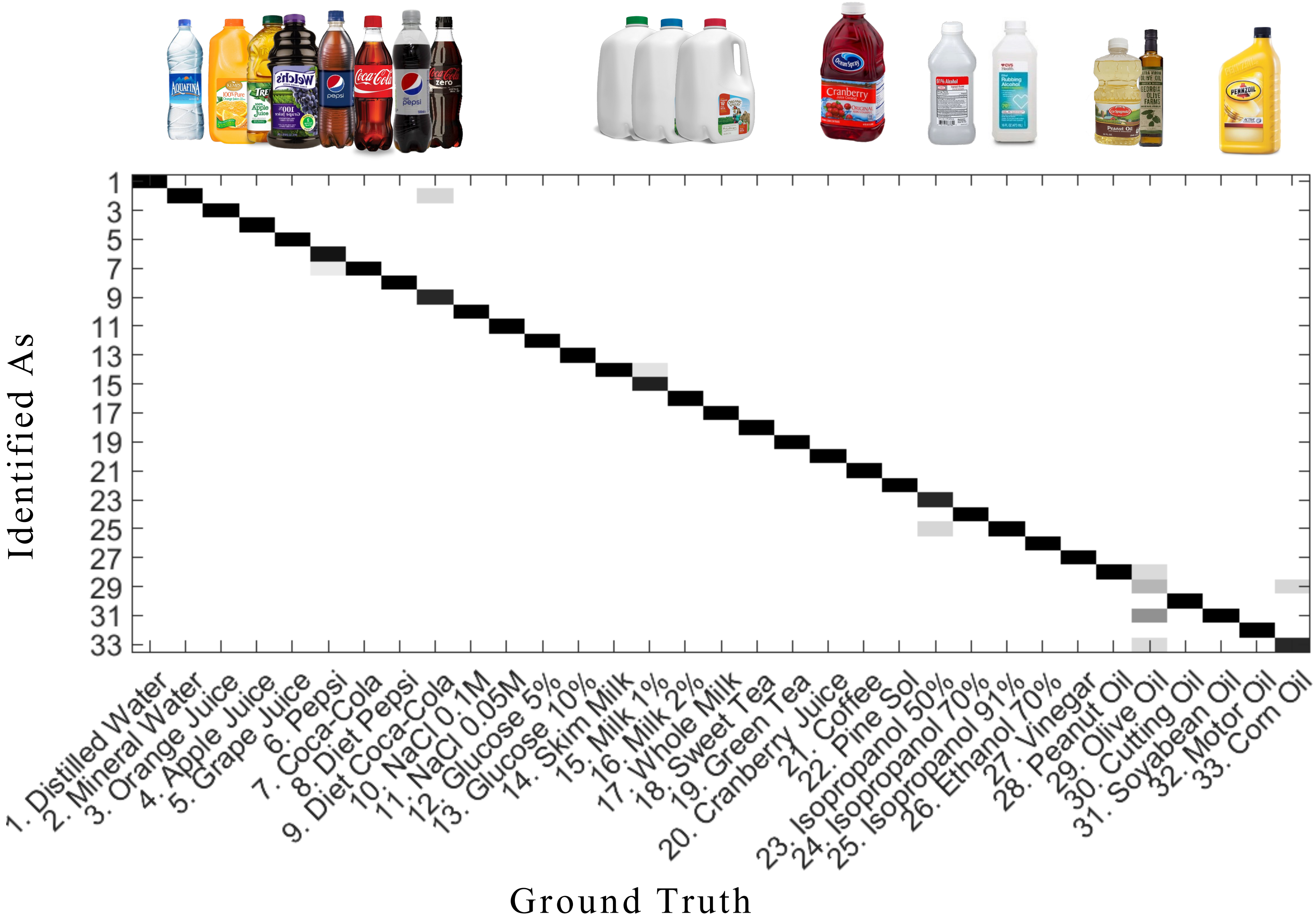
- Published error is 5%

Results – Permittivity





Results – Liquid Identification



Challenge: sensors for data-driven agriculture are expensive

Data-driven agriculture

> 100 USD

> 1000 USD

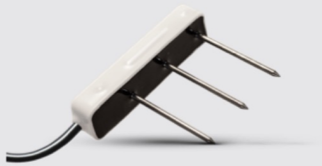
Price

Accuracy

Commercial-grade sensors

- Tensiometer

- Capacitance-based
- Resistivity-based



- Neutron probe
- Time domain reflectometry (TDR)
- Ground penetrating radar (GPR)

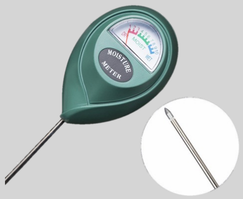
Challenge: sensors for data-driven agriculture are expensive

Data-driven agriculture

< 20 USD | > 100 USD | > 1000 USD | Price

Accuracy

Hobbyist sensors



Not reliable, degrade fast

Commercial-grade sensors

- Tensiometer

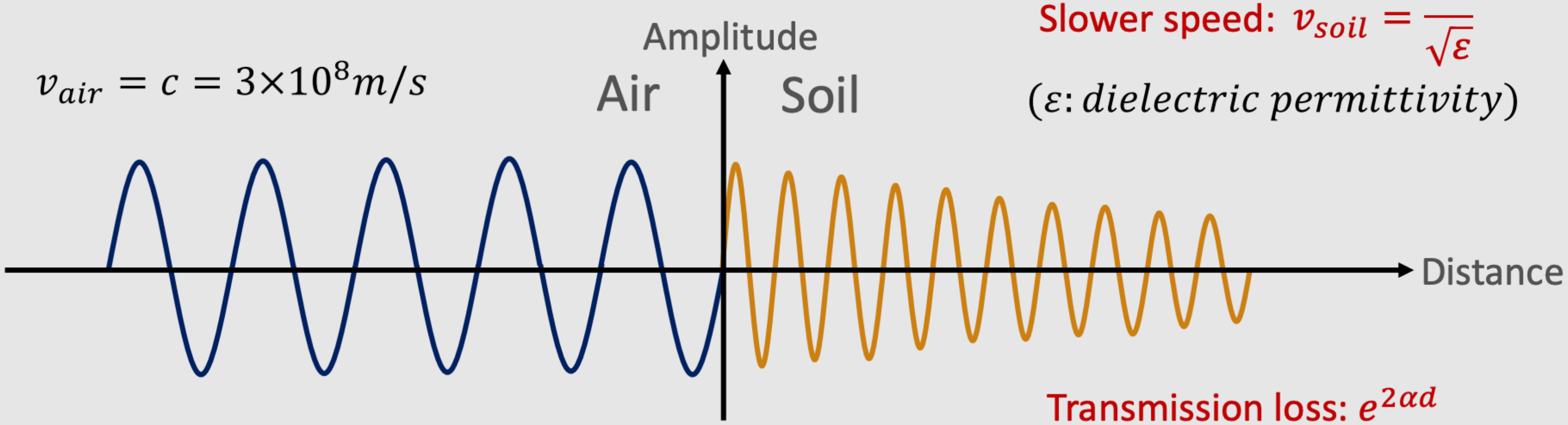
- Capacitance-based
- Resistivity-based

- Neutron probe
- Time domain reflectometry (TDR)
- Ground penetrating radar (GPR)

Idea: using RF signals

- Insight: RF wave in soil has a slower speed and higher attenuation

$v_{air} = c = 3\times10^{8} m/s$



Slower speed: $v_{soil} = \frac{c}{\sqrt{\varepsilon}}$

$(\varepsilon: dielectric\ permittivity)$

Transmission loss: $e^{2\alpha d}$

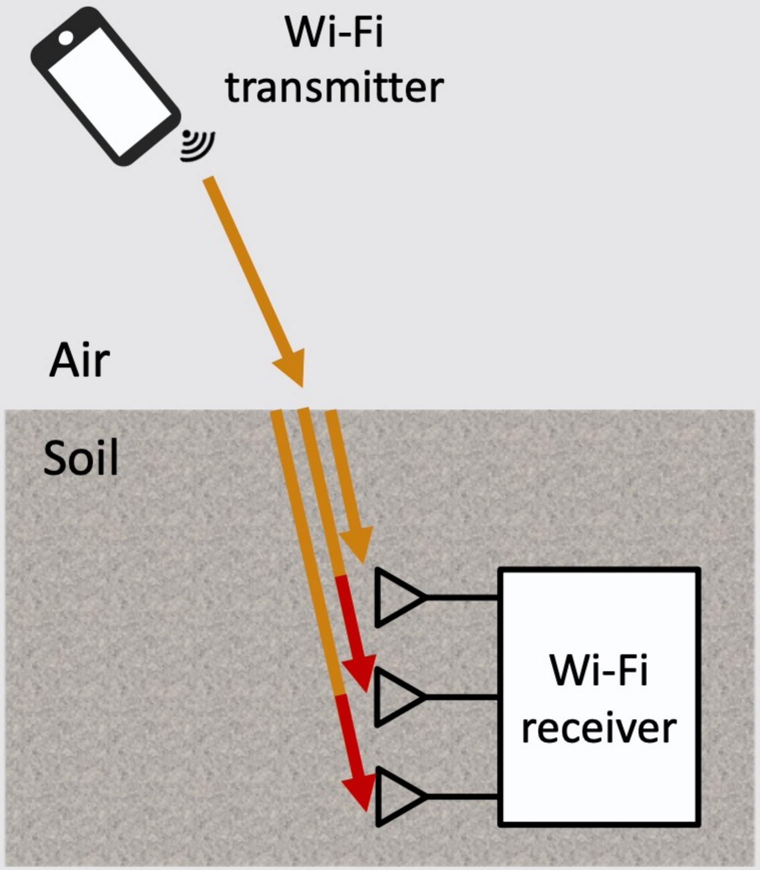
(α: $attenuation\ coefficient$, a function of EC)

Slower speed: due to higher dielectric permittivity (moisture)

Higher attenuation: due to extra transmission loss (EC)

Strobe: Enables **accurate** and **low-cost** soil sensing using Wi-Fi

- Addresses bandwidth & calibration challenges
  - Using multi-antenna array as RX
  - A novel algorithm based on **relative ToF and relative amplitude** between antennas
- Addresses the cost challenge by using commercial Wi-Fi devices
  - Single-antenna TX in air & multi-antenna RX array in soil



Strobe evaluation

- USRP – 1GHz bandwidth
- WARP & Wi-Fi card – 70 MHz bandwidth at 2.4 GHz

Waterproof box holding the RX antenna array

Soil boxes in a tent

Outdoor Wi-Fi steup

Liquid Testing with Your Smartphone

What is Liquid Testing?

Characterization of liquid type or concentration

Application I: Detect Water Contamination

Application II: Detect Proteinuria

- Diabetes
- High Blood Pressure

Excess protein in urine is a indicator for kidney disease

Application II: Detect Proteinuria

- Diabetes
- High Blood Pressure

disease

Can we deliver such applications to a normal user?

Today, liquid testing is done by experts in the lab

Our Goal: Liquid Testing with Smartphone

Almost everyone has a smartphone

Smartphone is portable

We are at MobiSys!

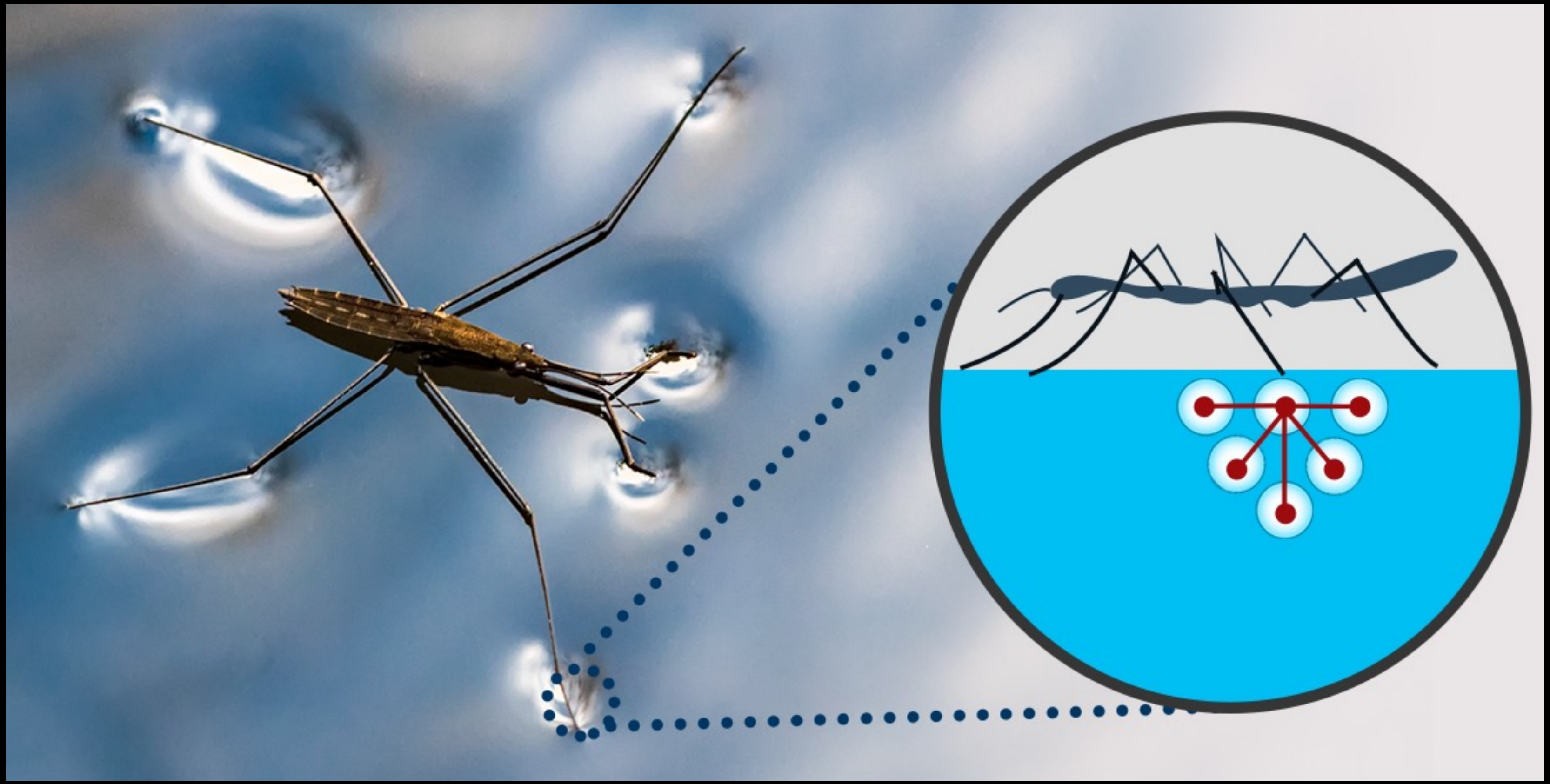
How?

Find a property that changes with liquid type and concentration

Find a method to measure this property with a smartphone

Property: Surface Tension

Force that holds surface molecules together



Surface tension characterizes liquid type and concentration

Clean Water: 72 mN/m

15% Alcohol: 42 mN/m

Contamination with bacteria, oil, etc reduces surface tension

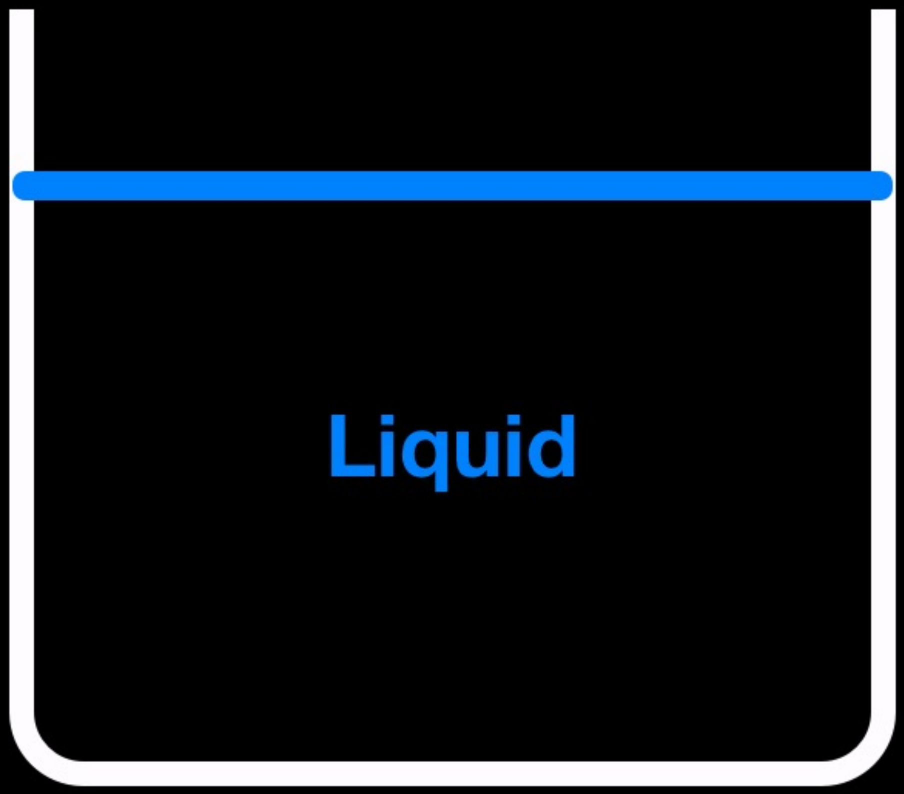
Increasing alcohol concentration reduces surface tension

Protein reduces surface tension

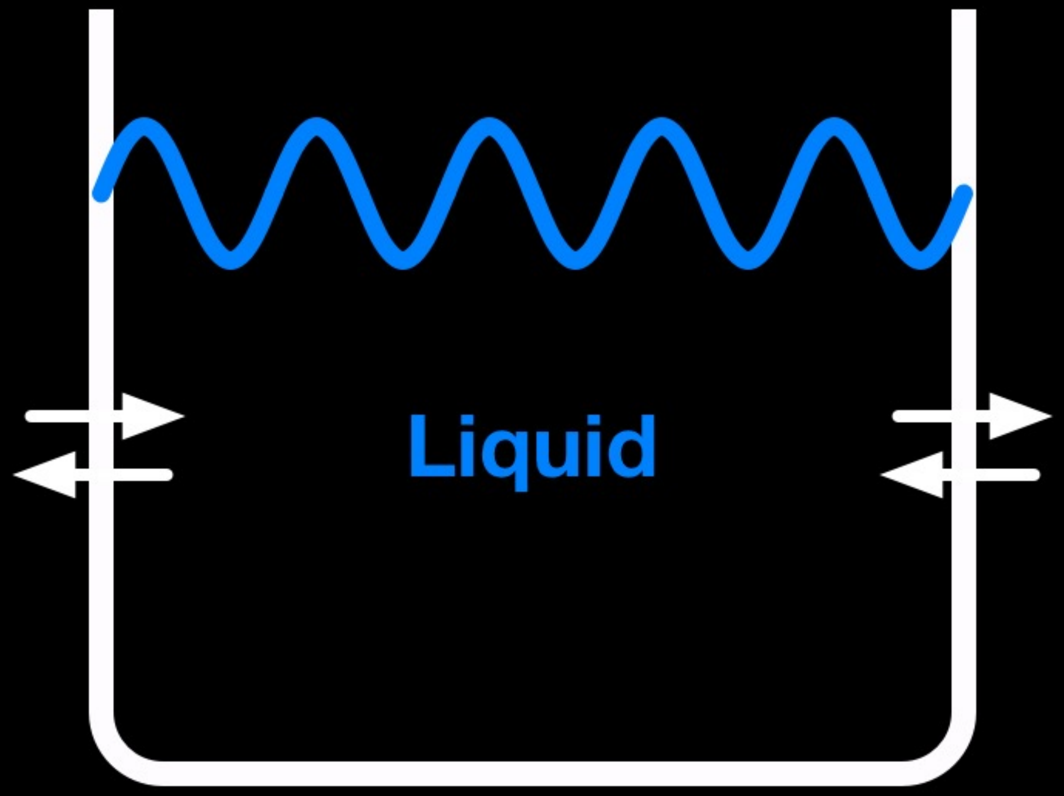
How do we measure surface tension with a smartphone?

CapCam: First mobile app for measuring surface tension

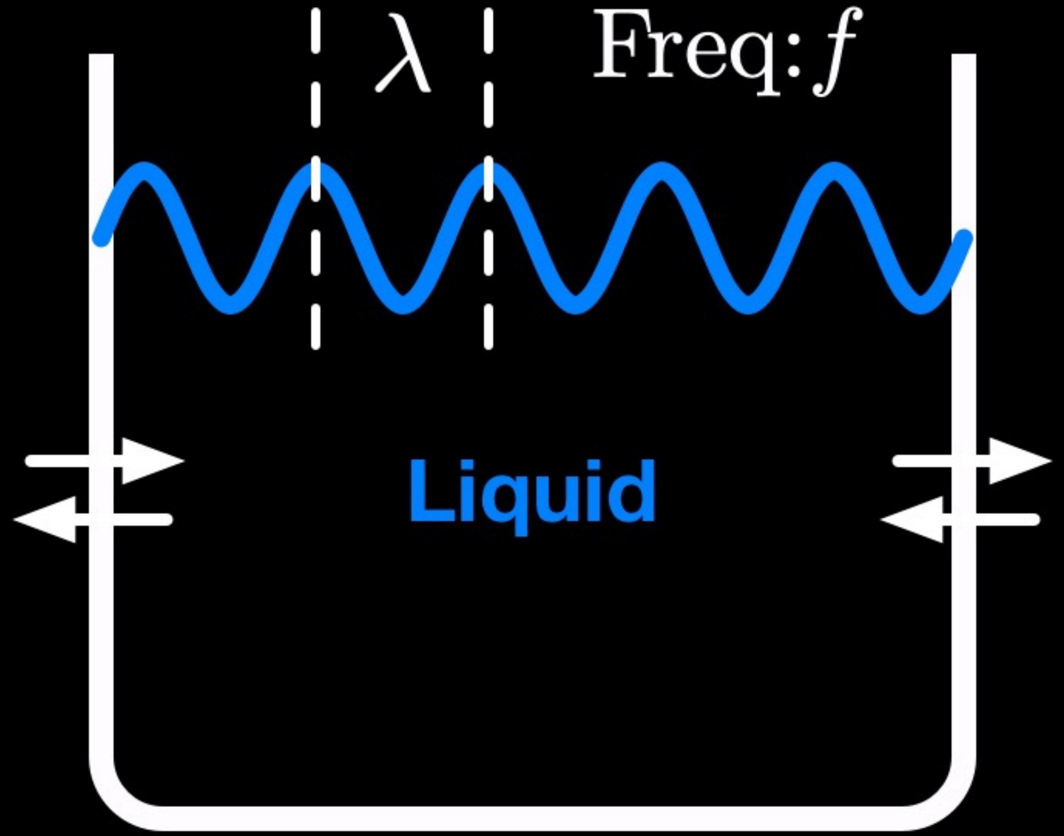
Measuring surface tension



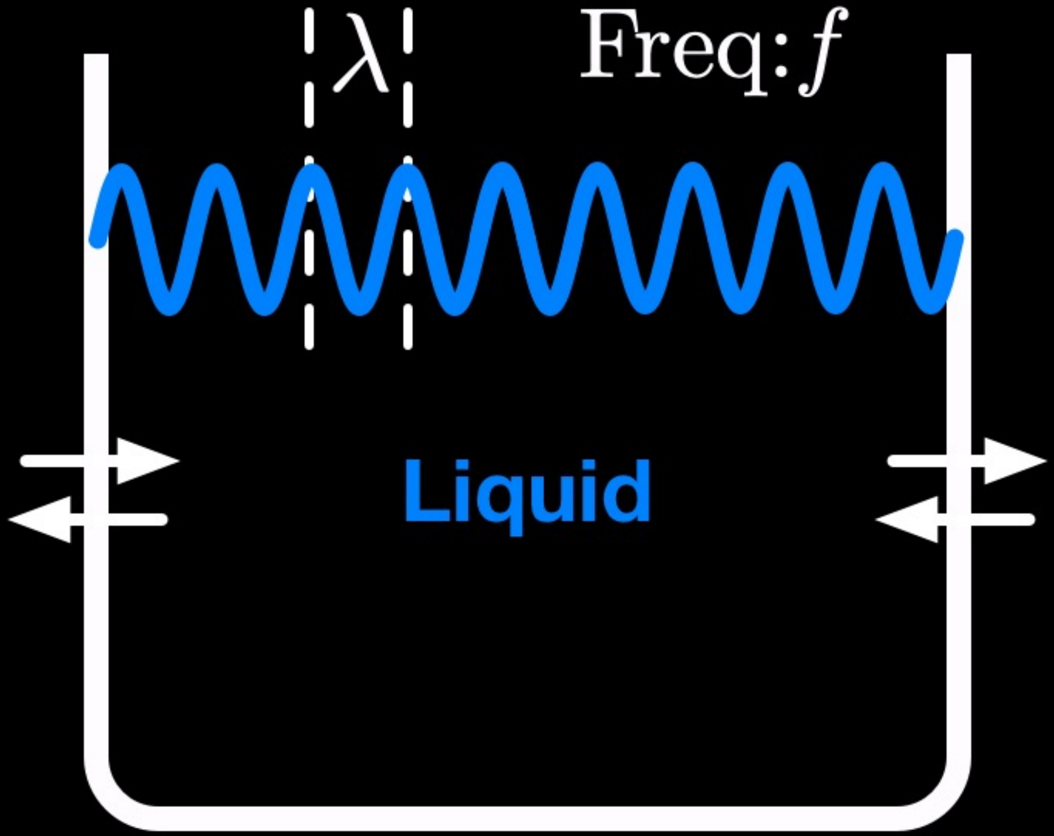
Measuring surface tension



Measuring surface tension

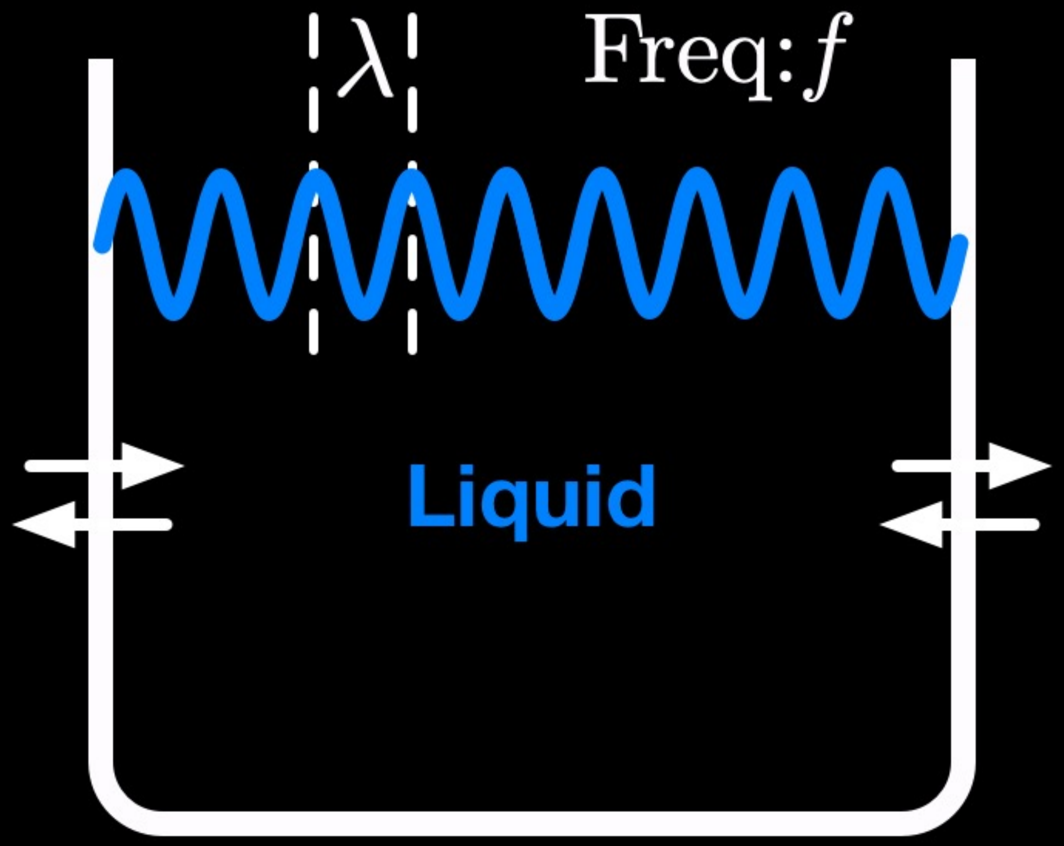


Measuring surface tension



Measuring surface tension

Measuring surface tension : Capillary Waves

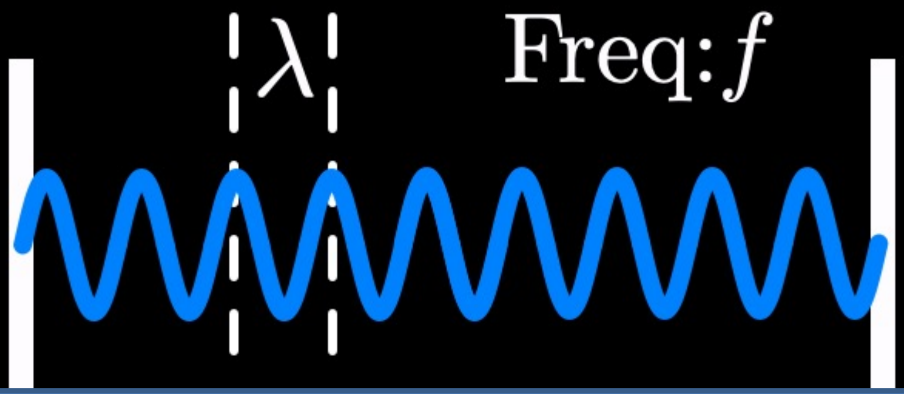


$$\gamma \propto f^2 \cdot \lambda^3$$

- γ : Surface tension
- λ : Wavelength
- f : Frequency

Measuring surface tension

Measuring surface tension : Capillary Waves



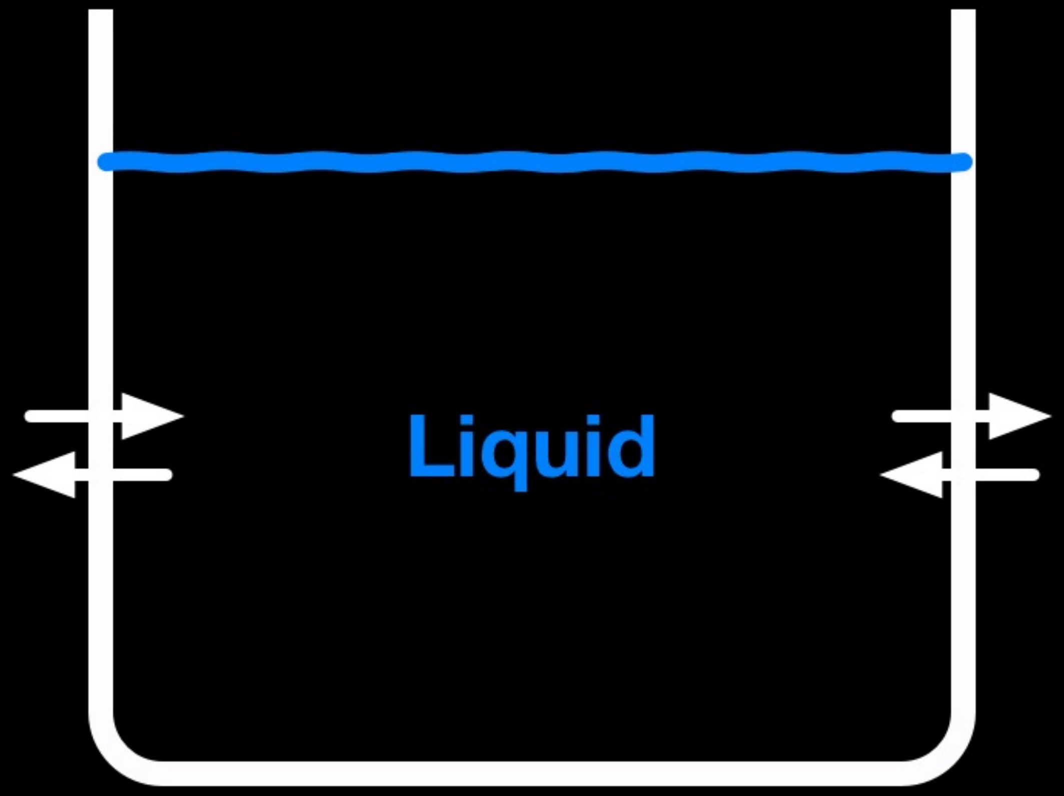
$$\gamma \propto f^2 \cdot \lambda^3$$

Idea:

Vibrate the container with phone’s vibro-motor

Use phone’s camera to measure the wavelength

Challenge I: Amplitude of wave is small



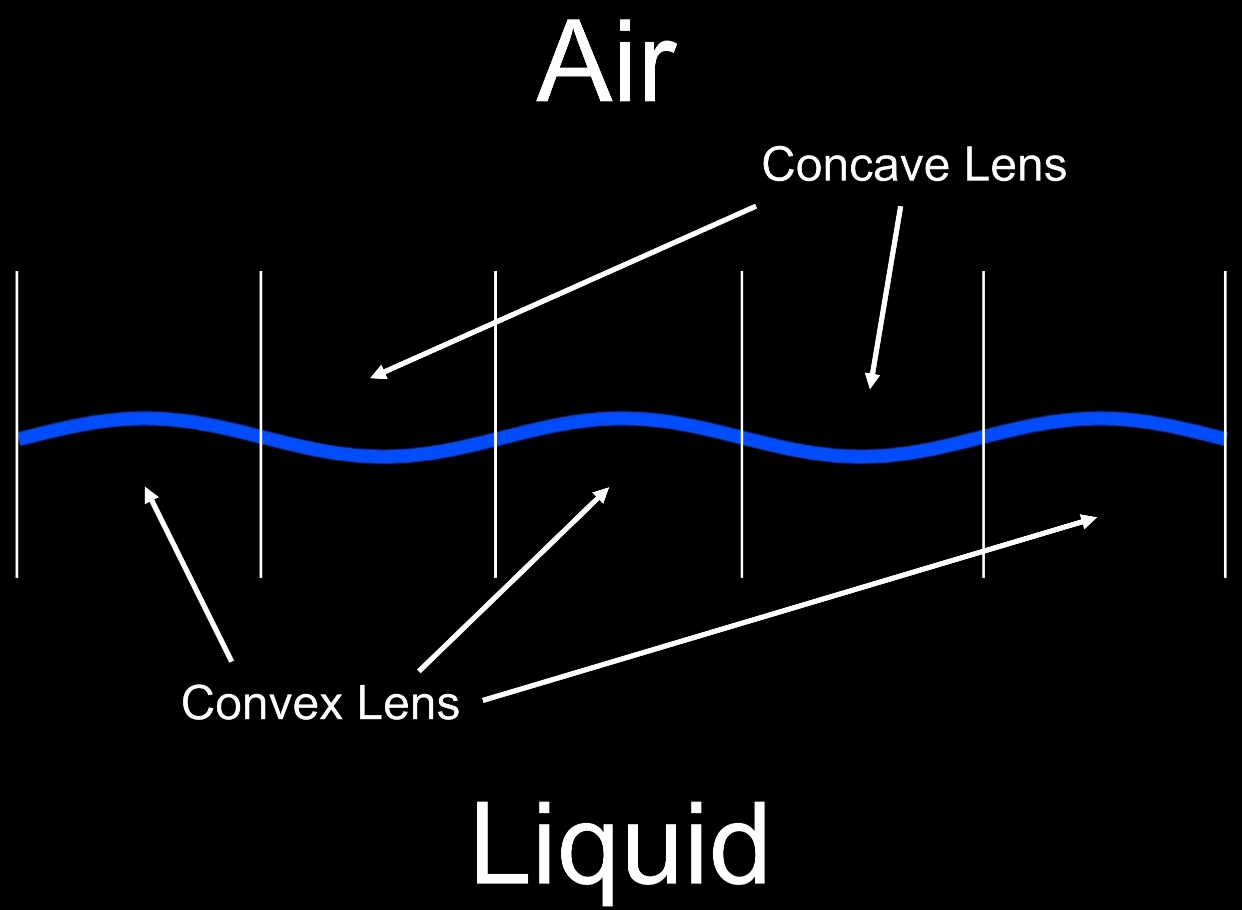
Problem:

Amplitude is really small ($\sim 10^{-6}\ m$)

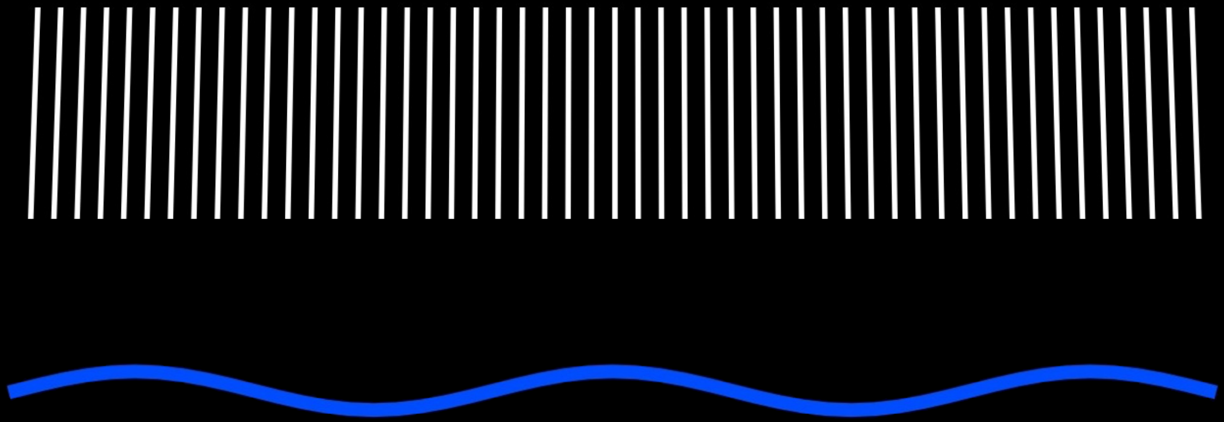
Solution:

Create lens effects

Create Lens Effect

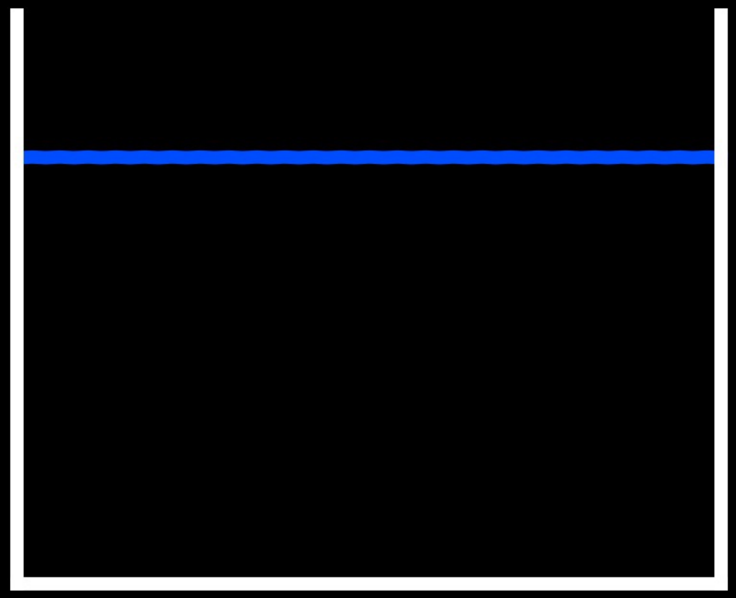


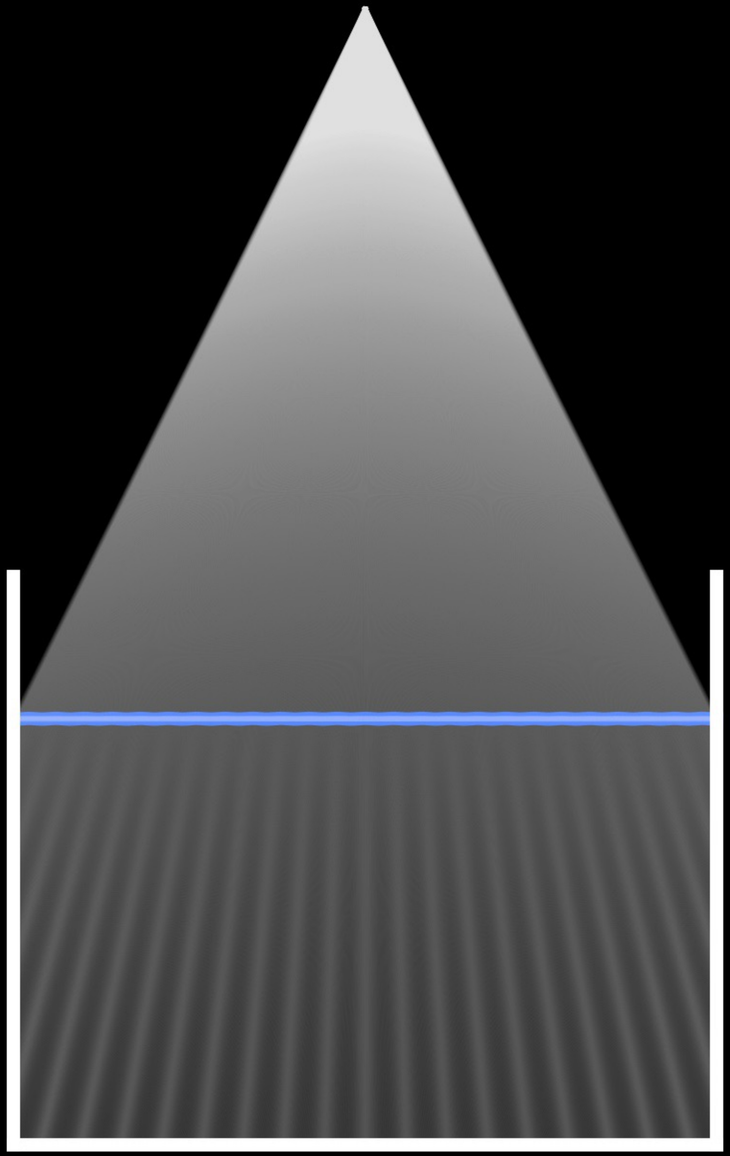
Create Lens Effect



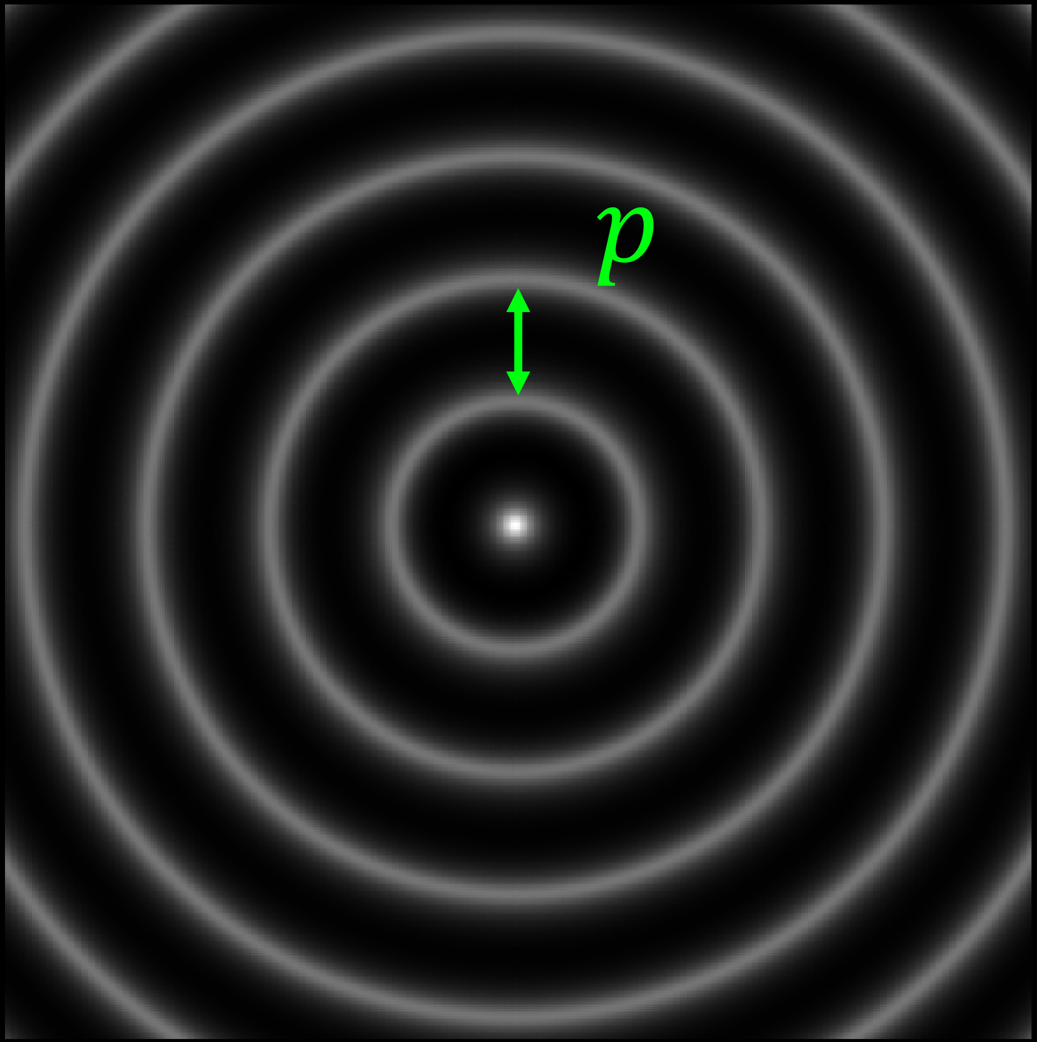
Create Lens Effect

Tiny Waves!



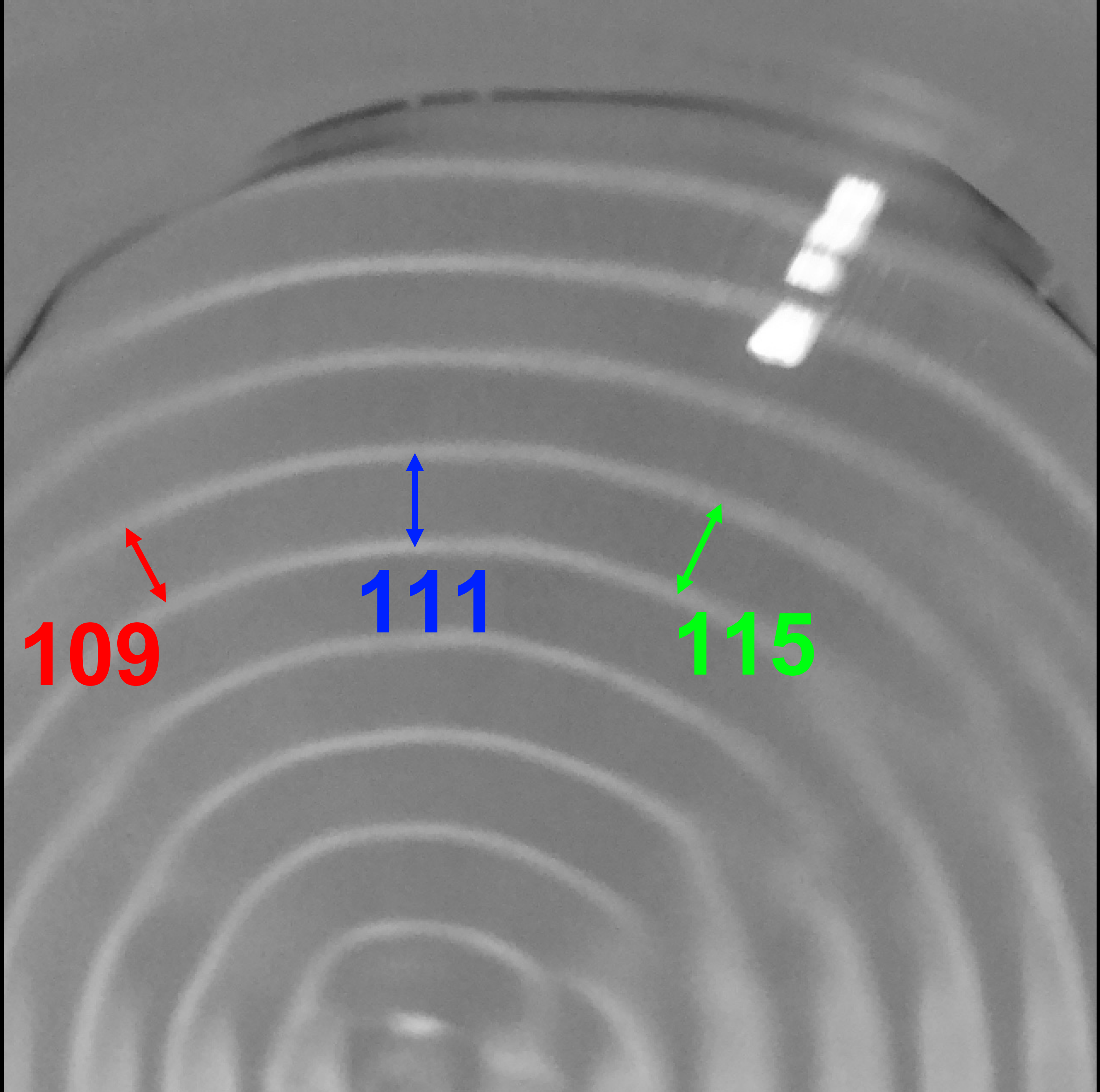



Wavelength Inference

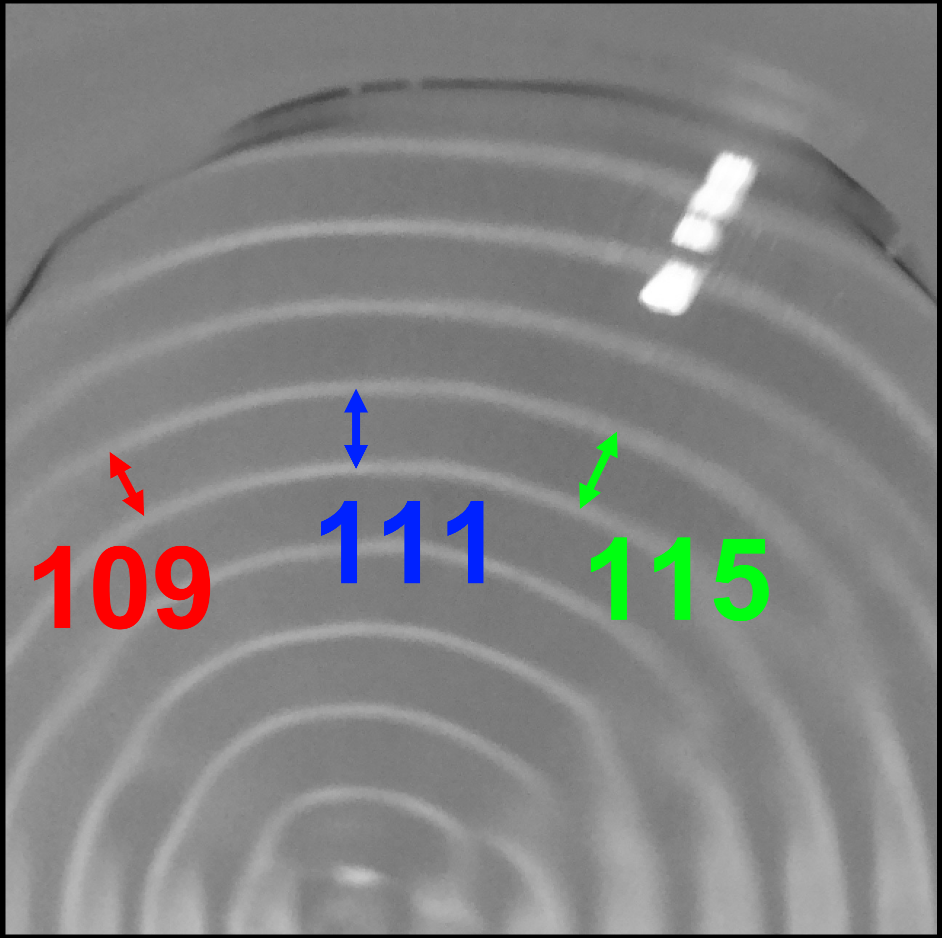


$$\lambda = p/\mathrm{r}(d)$$

- $r(x)$: Camera's resolution at distance x
- d: Distance between camera and the surface of the liquid

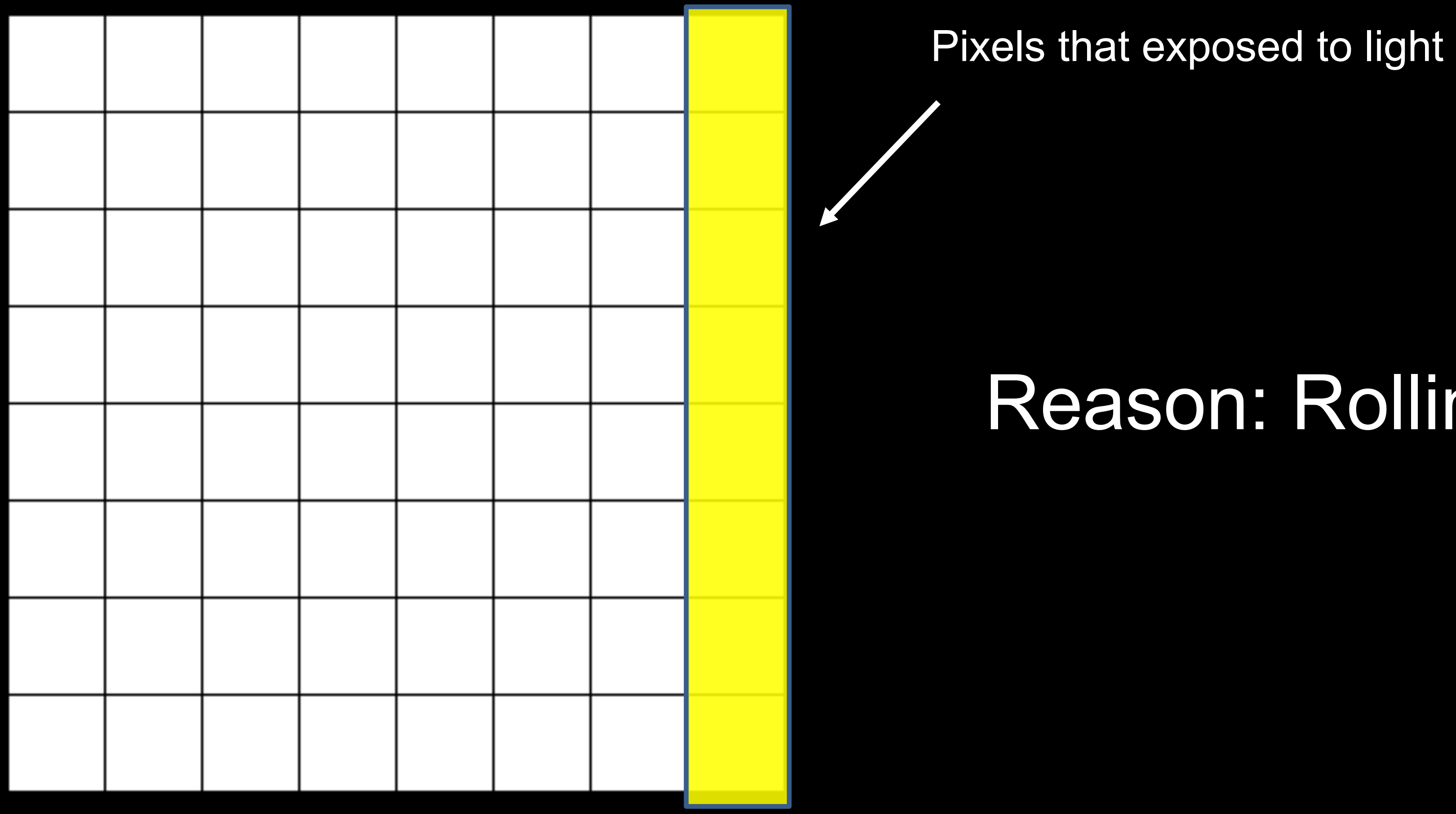

109
111
115

Challenge II: Camera Artifacts



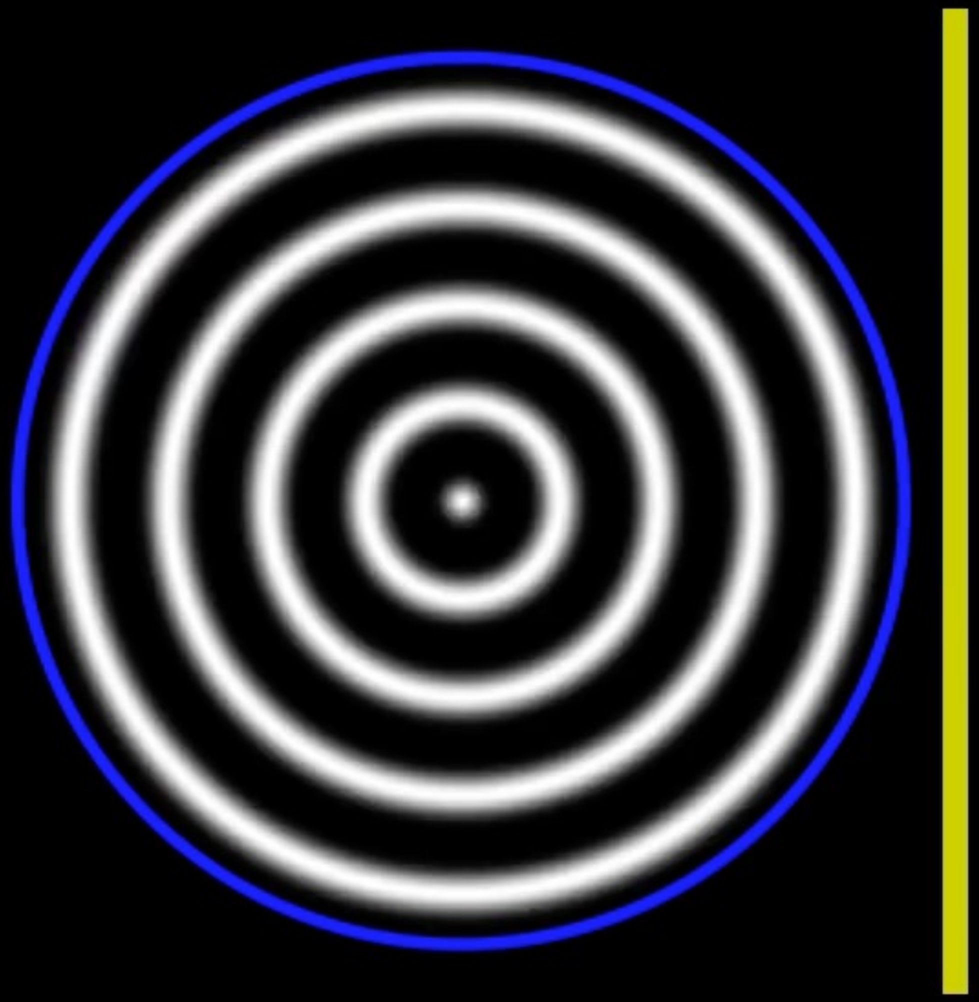
Problem:
Wavelengths along different directions are different

Challenge II: Camera Artifacts

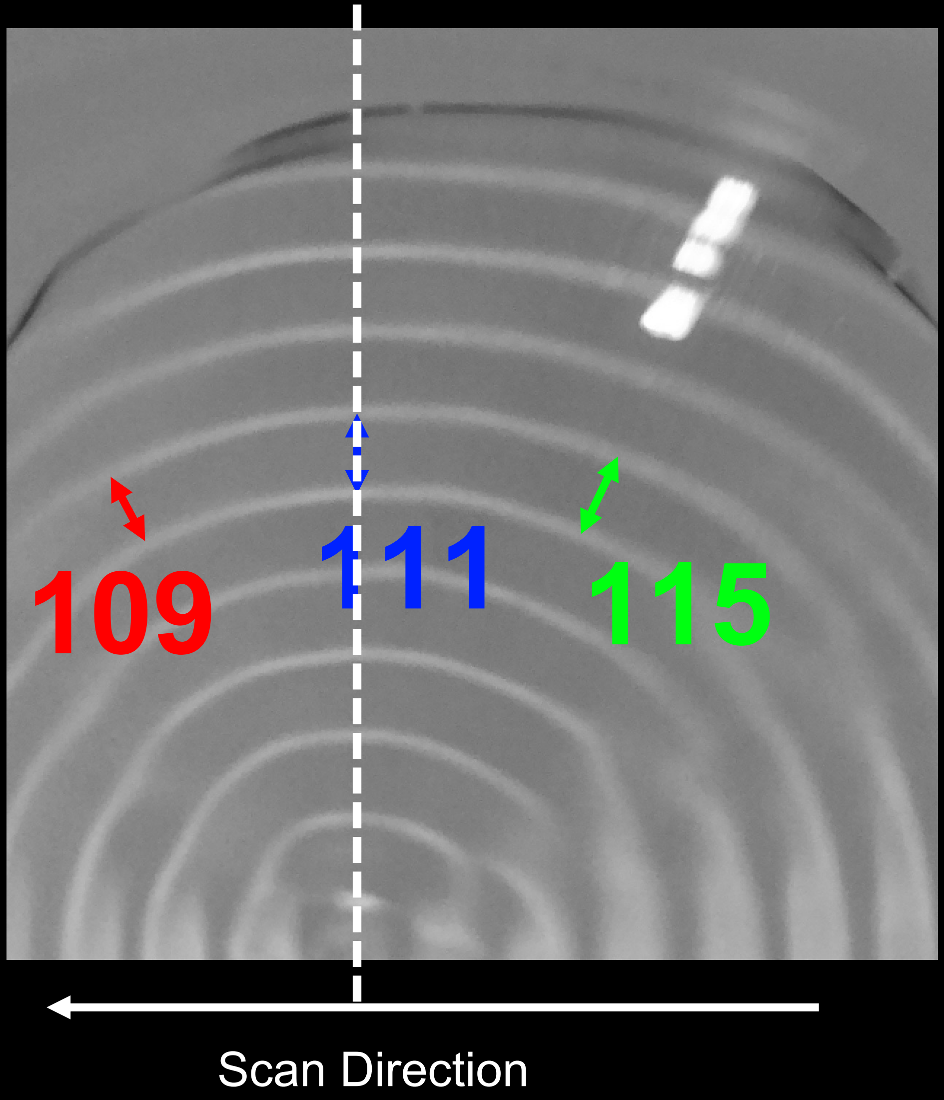


Reason: Rolling Shutter

Rolling Shutter Demo



Challenge II: Camera Artifacts



Solution:

- Pick direction that orthogonal to the scanning direction
- Using wavelet filtering to automatically detect correct location


11:50
CapCam
Storage
Distance: (Ruler)
87
mm
Density:
1.0
g/cm³
Total Images:
200
pics
Light
Vibrate
Start!

CapCam - Demo

https://youtu.be/LGBXy6BqIiE

Evaluation

Detect water contamination

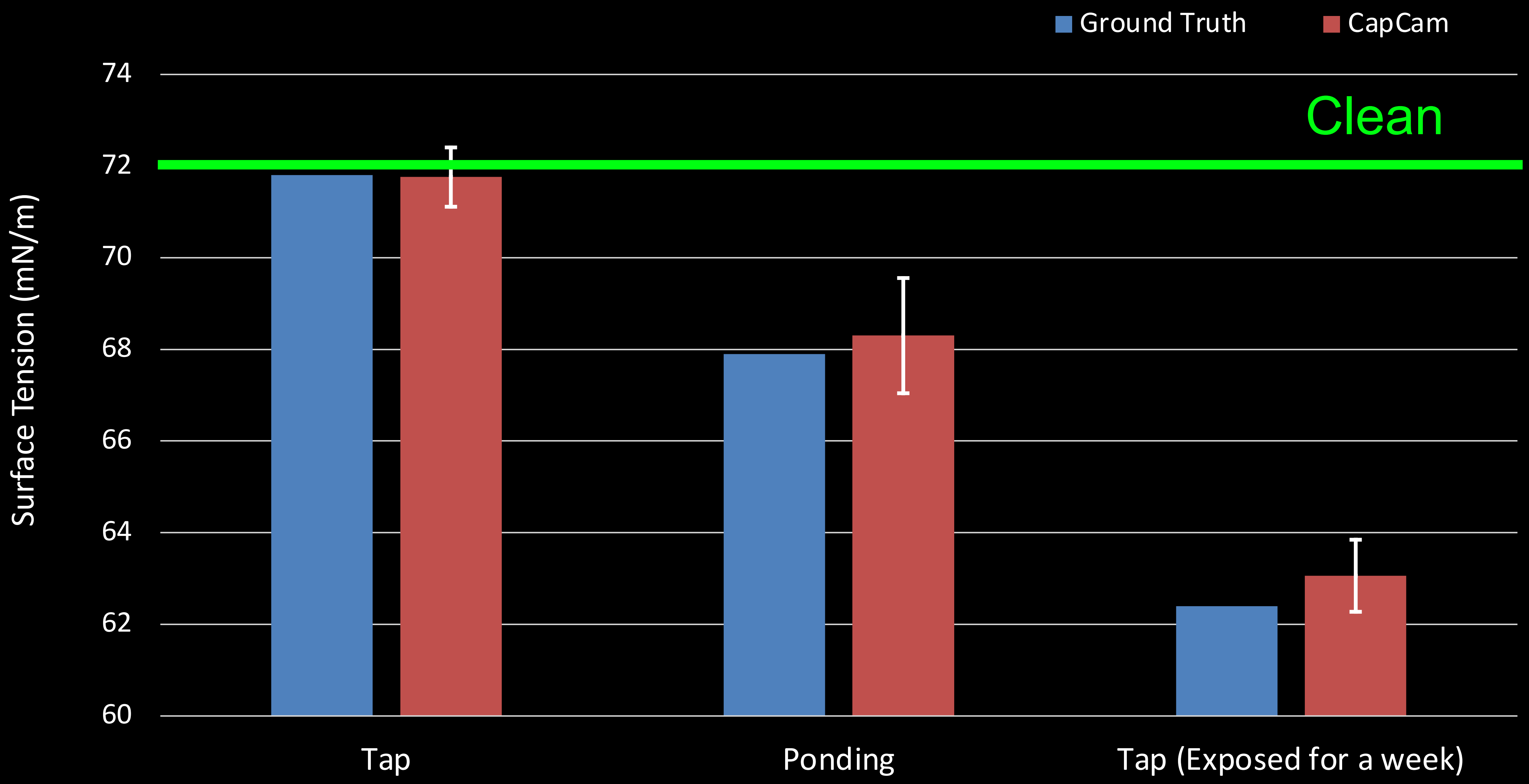
Track protein level in urine

Measure alcohol concentration level

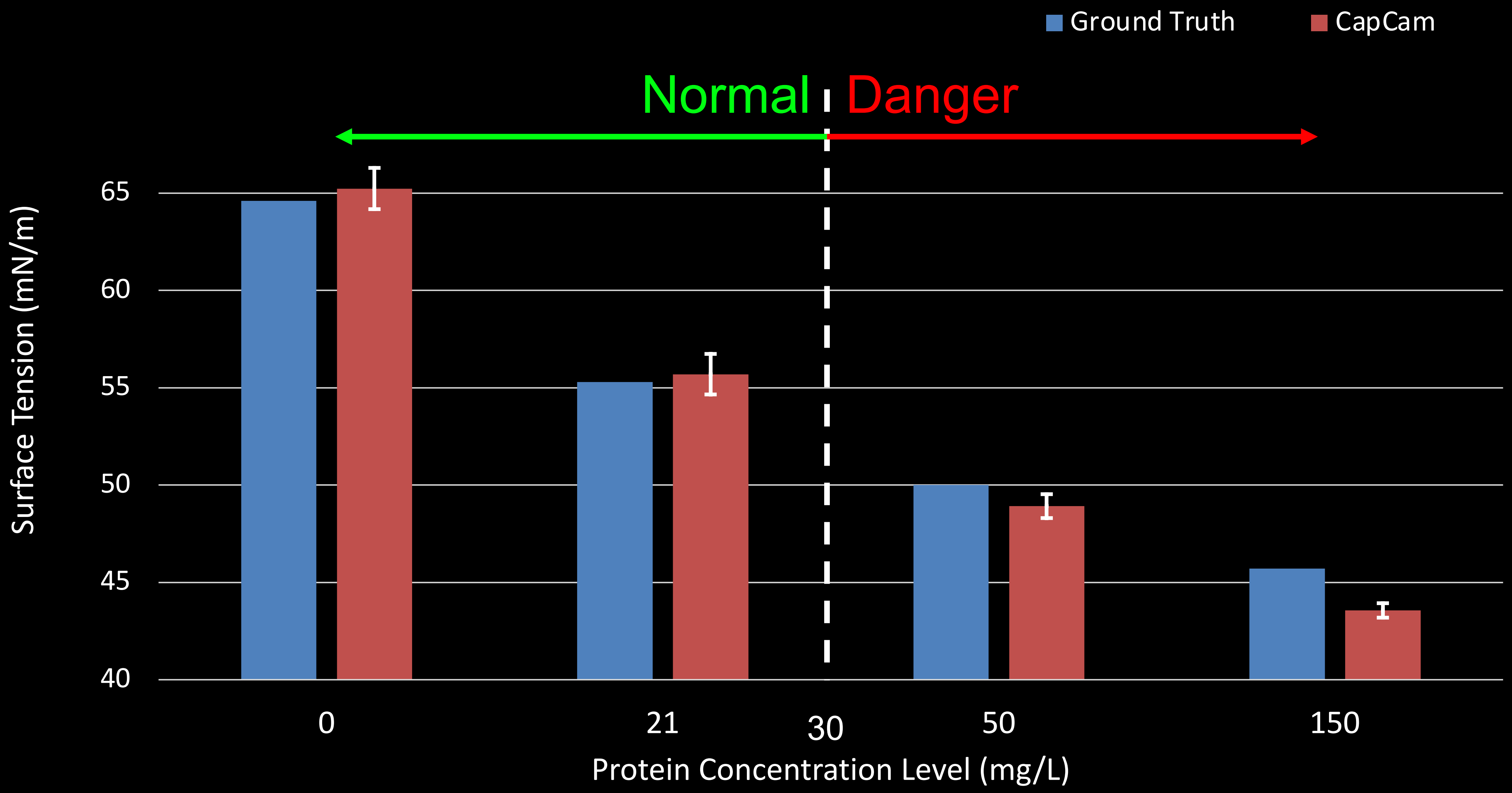
Ground Truth - Digital Tensiometer

- Resolution: 0.1 mN/m
- Cost $10,000+
- Complicated to operate

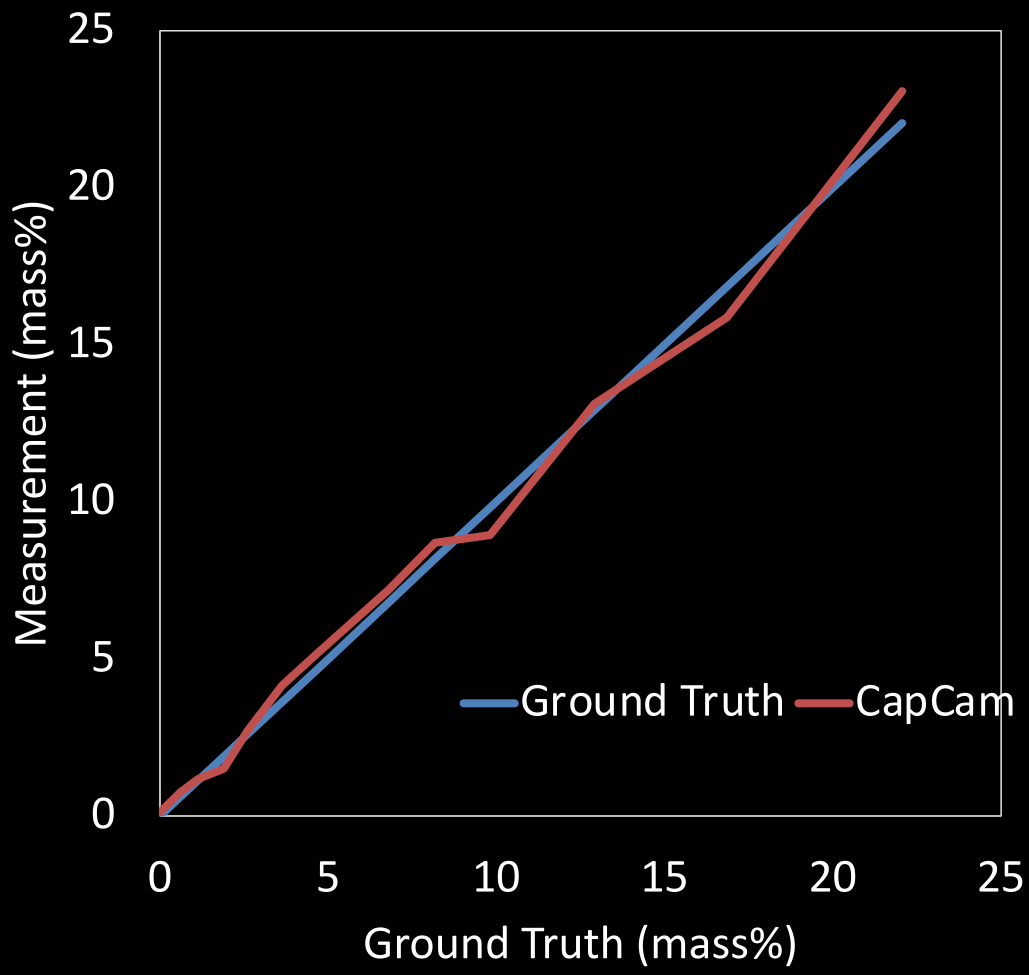
Water Contamination



Protein Level in Urine



Alcohol Concentration Level



The absolute error is only 0.51%.

Resolution of other studies >= 20%

[Rahman, et al. 2016, Ha, et al. , 2018]

Conclusion

- CapCam estimates surface tension with only a phone

- CapCam show its efficacy on multiple applications

For the paper, slides and demo: http://people.csail.mit.edu/scyue/projects/capcam/