Wireless Sensing

*Slides in this lecture are courtesy of Haitham Hassanieh, Ashutosh Dhekne, Unsoo Ha, and Jian Ding

Can we sense food and liquids in closed containers?

Is it safe?

Is it authentic?

Has it expired?

Applications

The New York Times

ASIA PACIFIC

China's Top Food Quality Official Resigns

By DAVID BARBOZA SEPT. 22, 2008

A baby suffering from kidney stones after drinking tainted formula was treated Monday at a hospital in Chengdu, China. China Photos, via Getty Images

SHANGHAI — The chief of China's food and product quality agency was forced to resign Monday in a growing scandal over the country's tainted milk supply, which has already sickened more than 50,000 infants and killed at least three children, according to the state-run Xinhua news agency.

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The Observer Wine

The great wine fraud

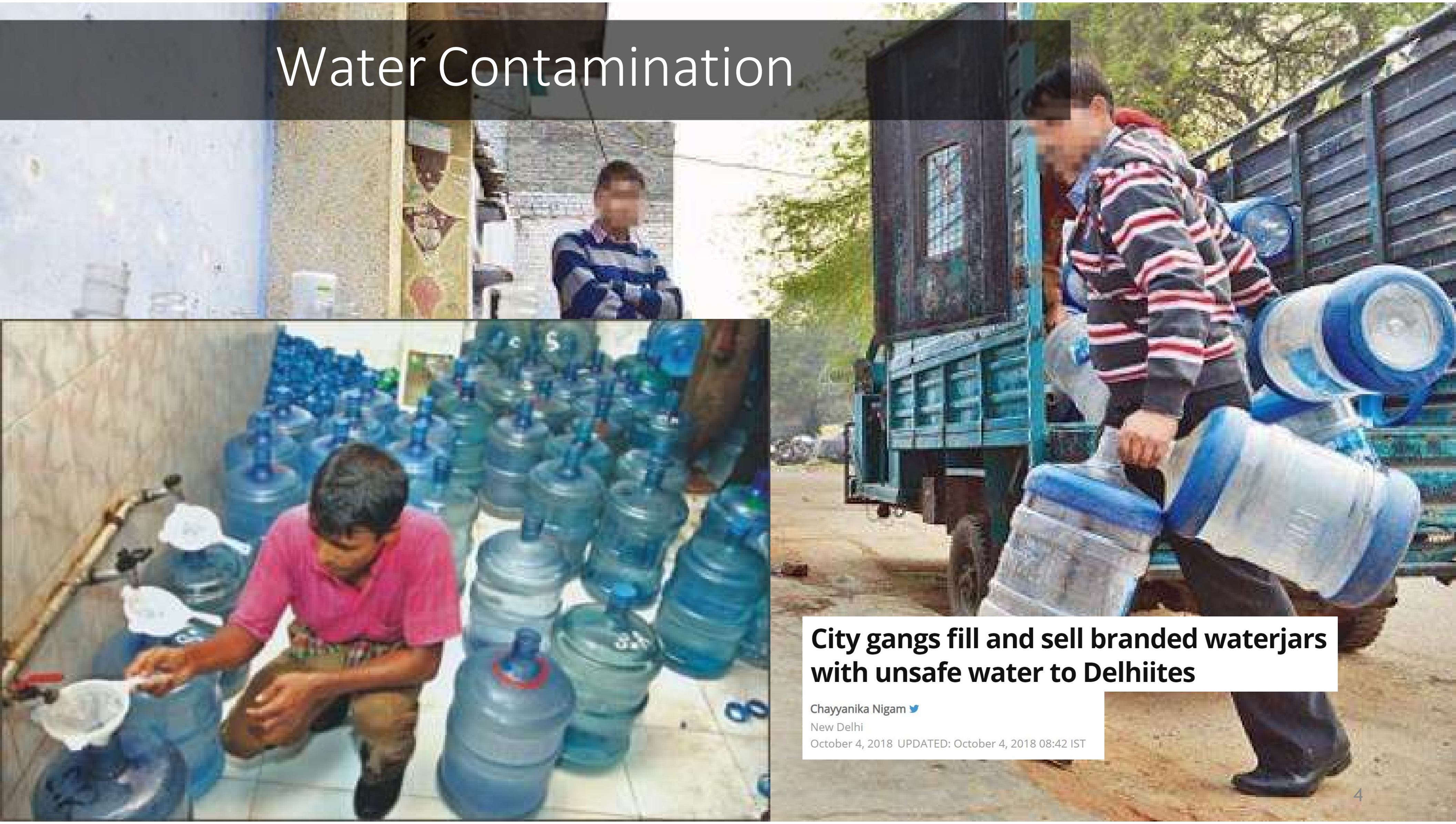
Rudy Kurniawan amassed a vast fortune trading in rare wines. Trouble is, he was bottling them himself. Ed Cumming reports on a vintage swindle

Ed Cumming
Sat 10 Sep 2016 19.05 EDT

World

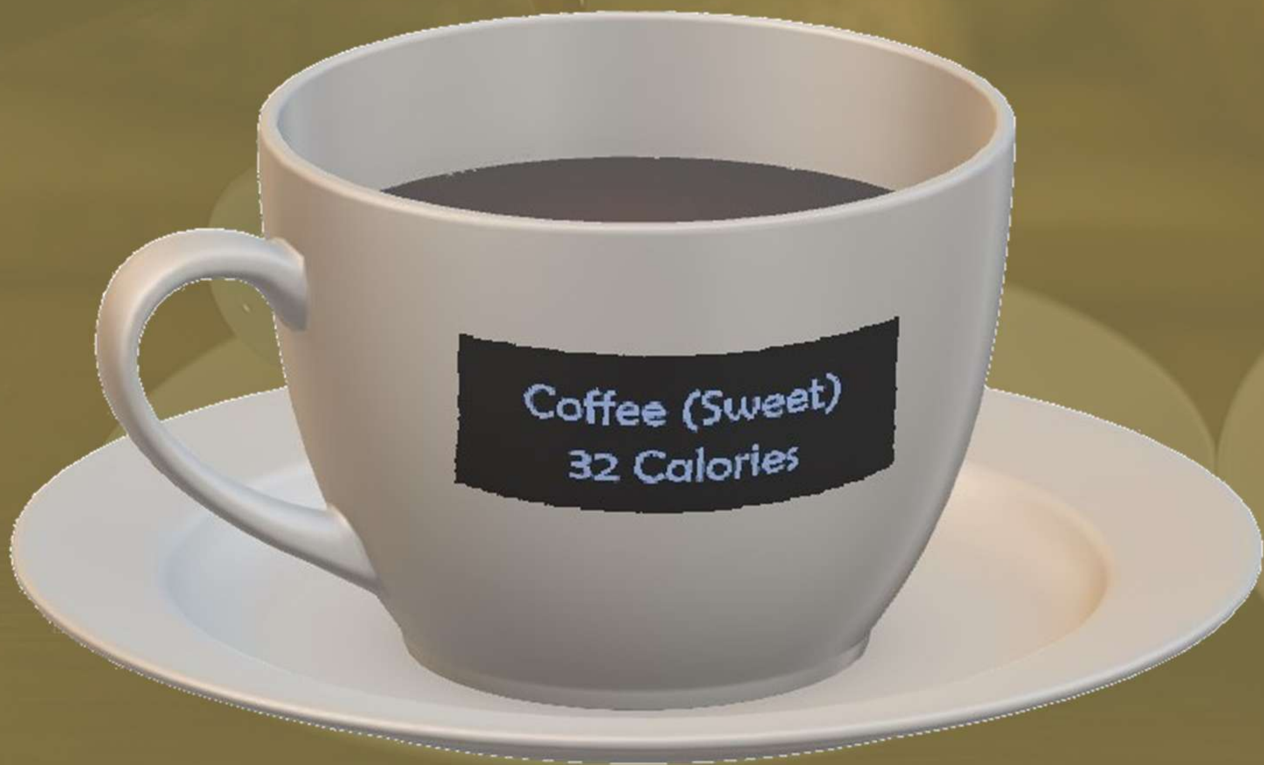
Fake drugs kill people and fund terror. African leaders hope to do something about it.

Water Contamination



Airport Security

Calorie Cup



LiquID: Wireless Sensing Liquids

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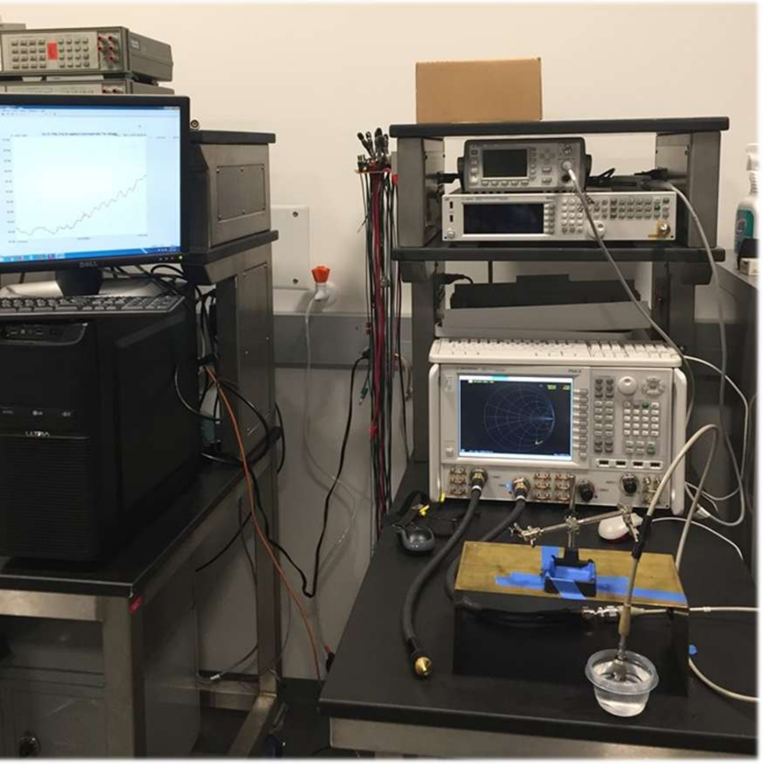
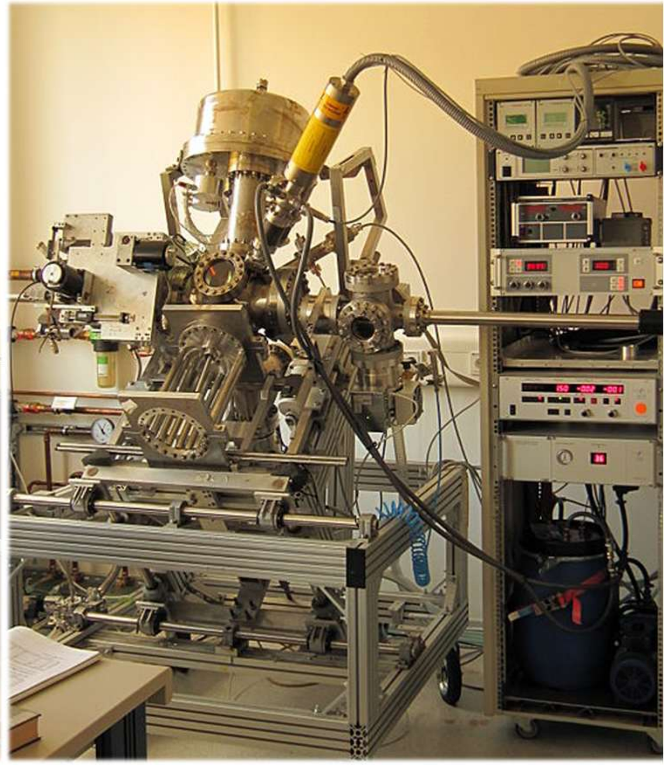
Existing Solutions



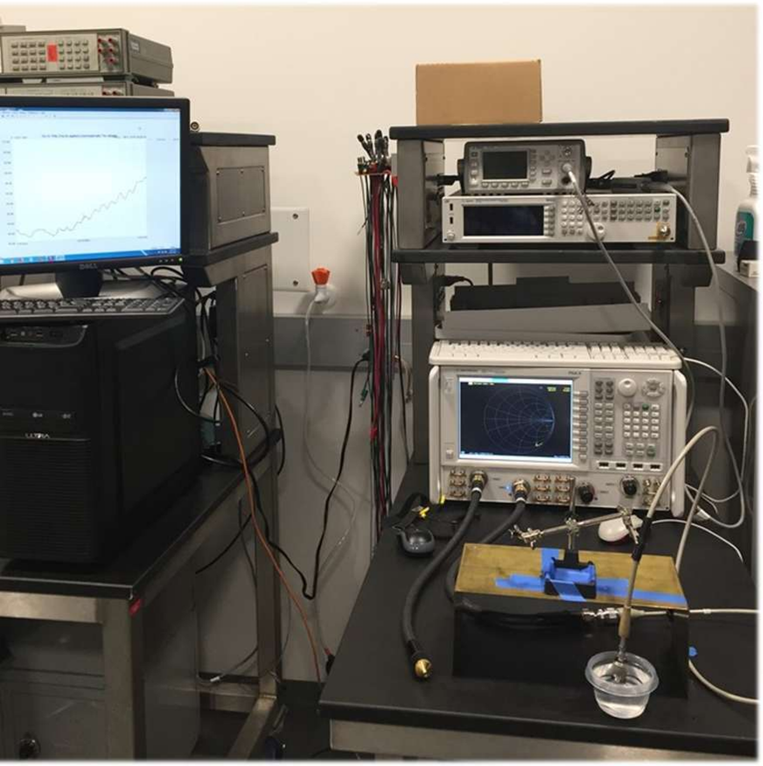


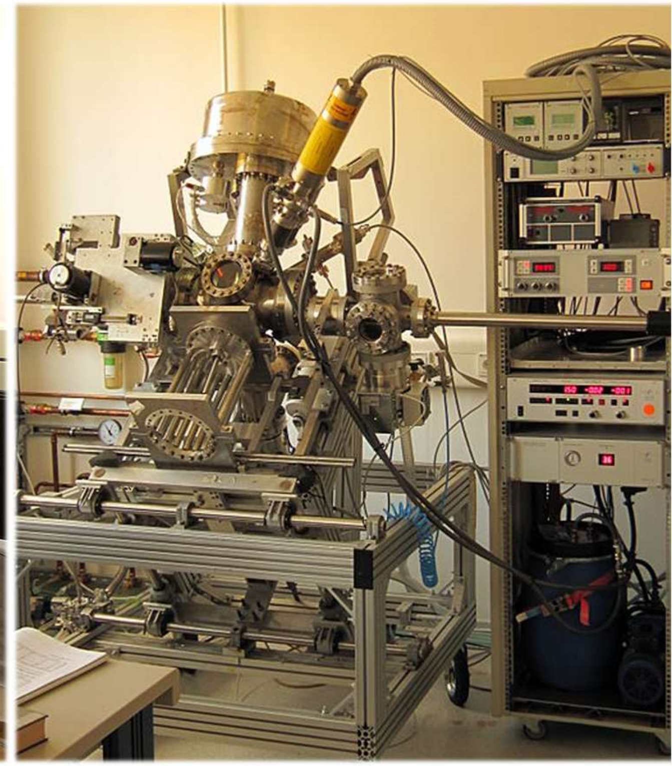
Existing Solutions

Dipping a Probe: Invasive

Chemical Analysis: Destructive

Expensive ($50k +) and Bulky: Inconvenient





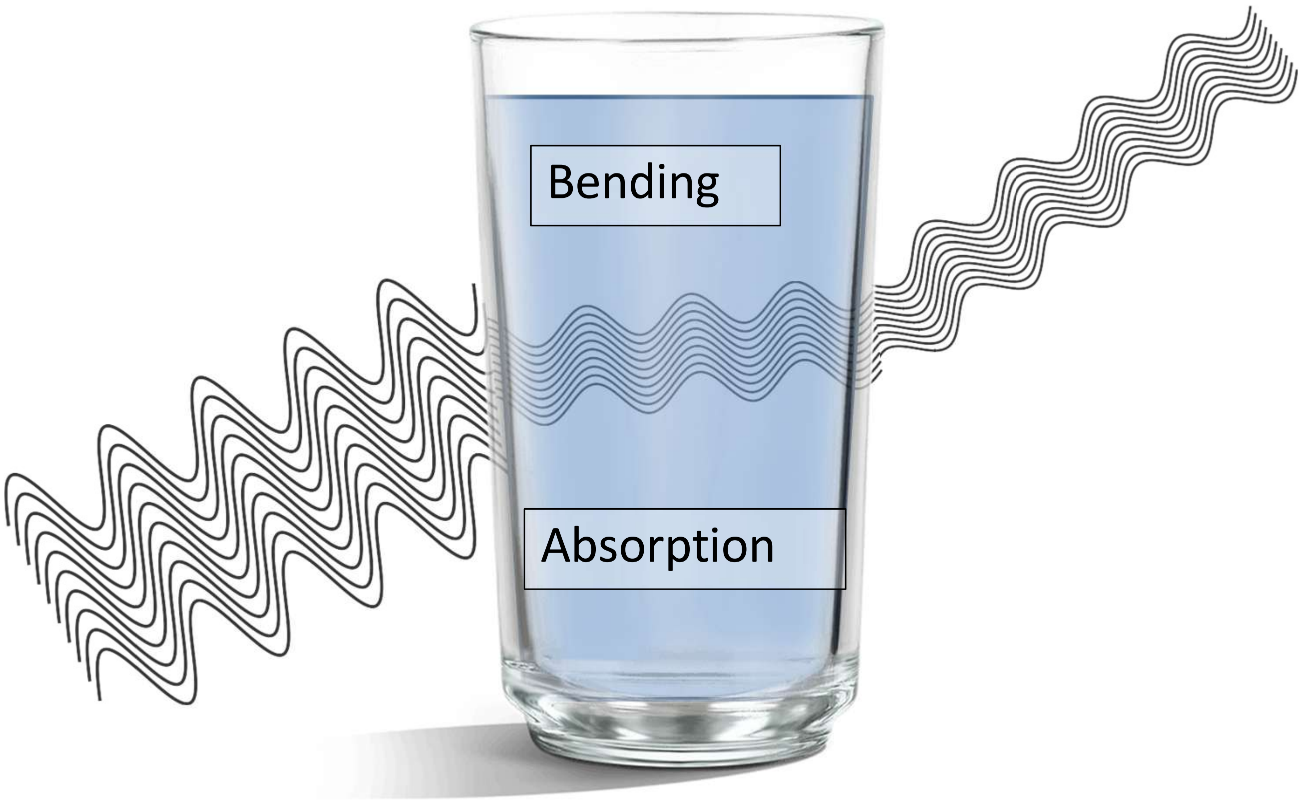
✓ Identify liquids without touching it: Non-invasive

✓ Using low power, wireless signals: Non-destructive

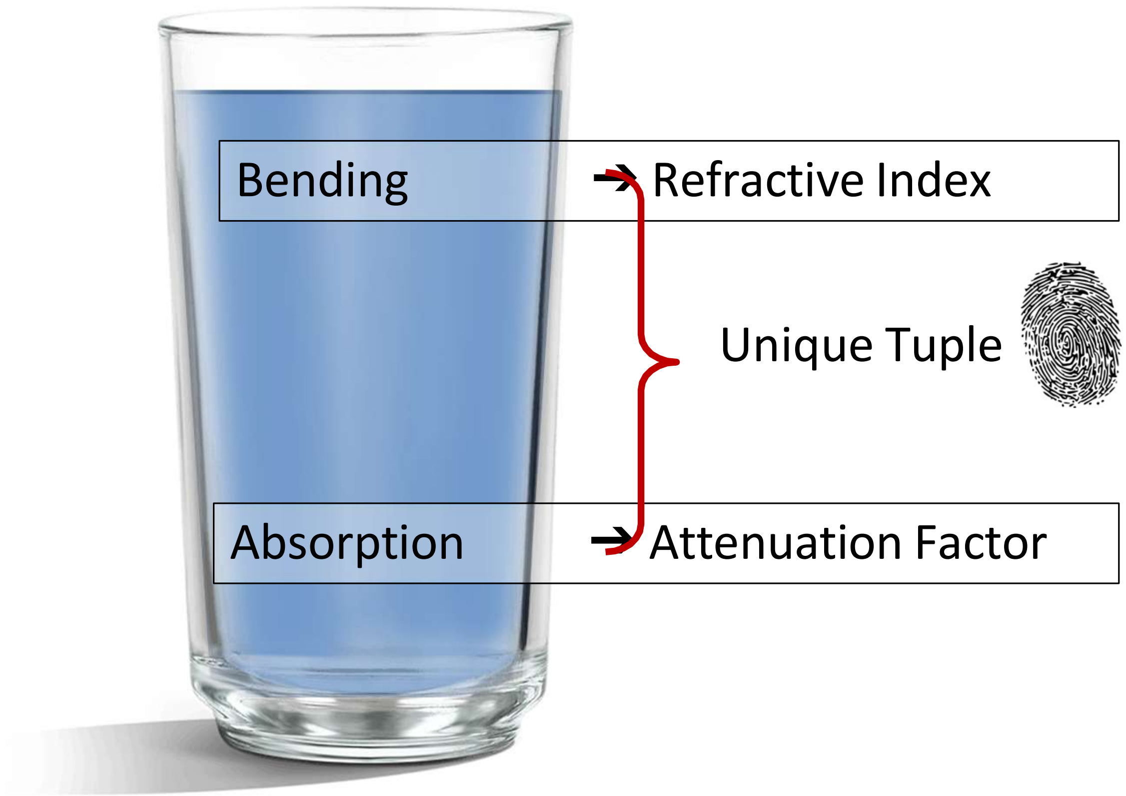
✓ Small and cheap: IoT

How ?

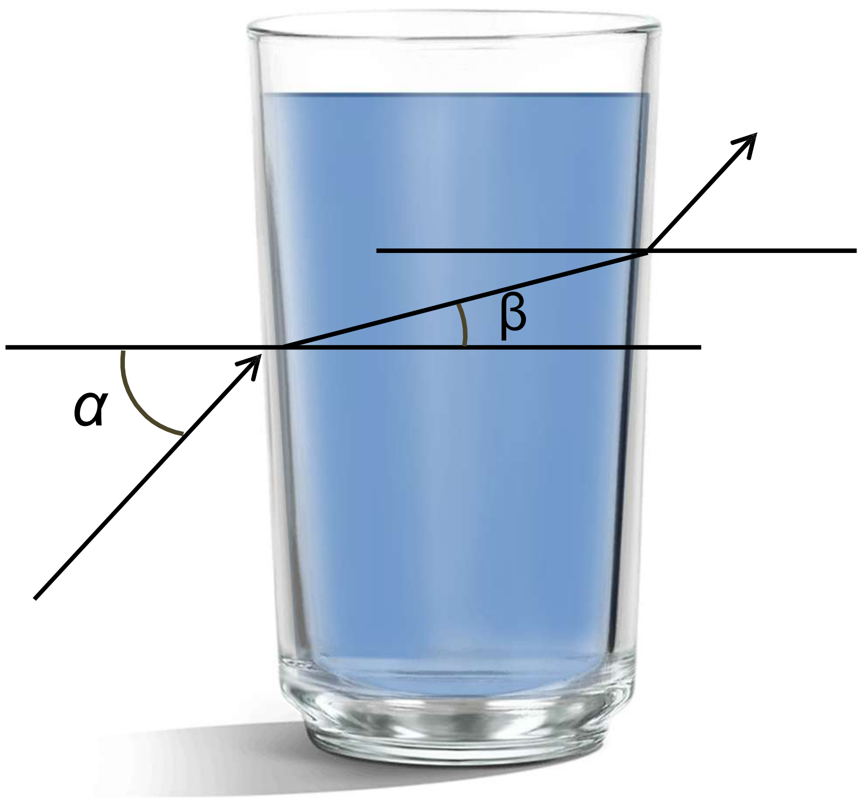
Key Properties of Liquid



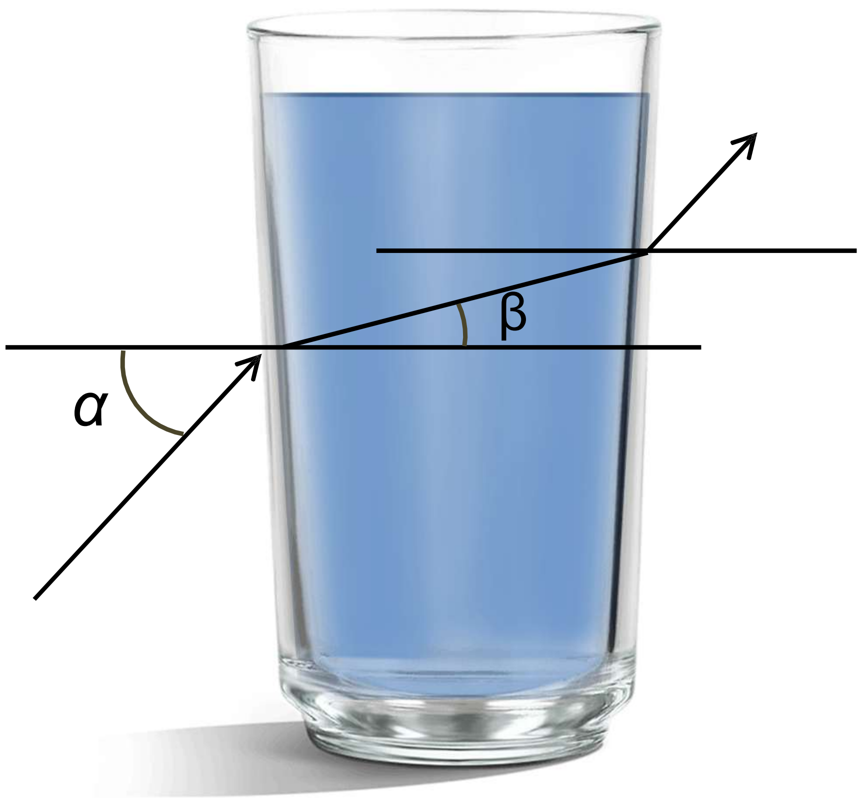
Key Properties of Liquid

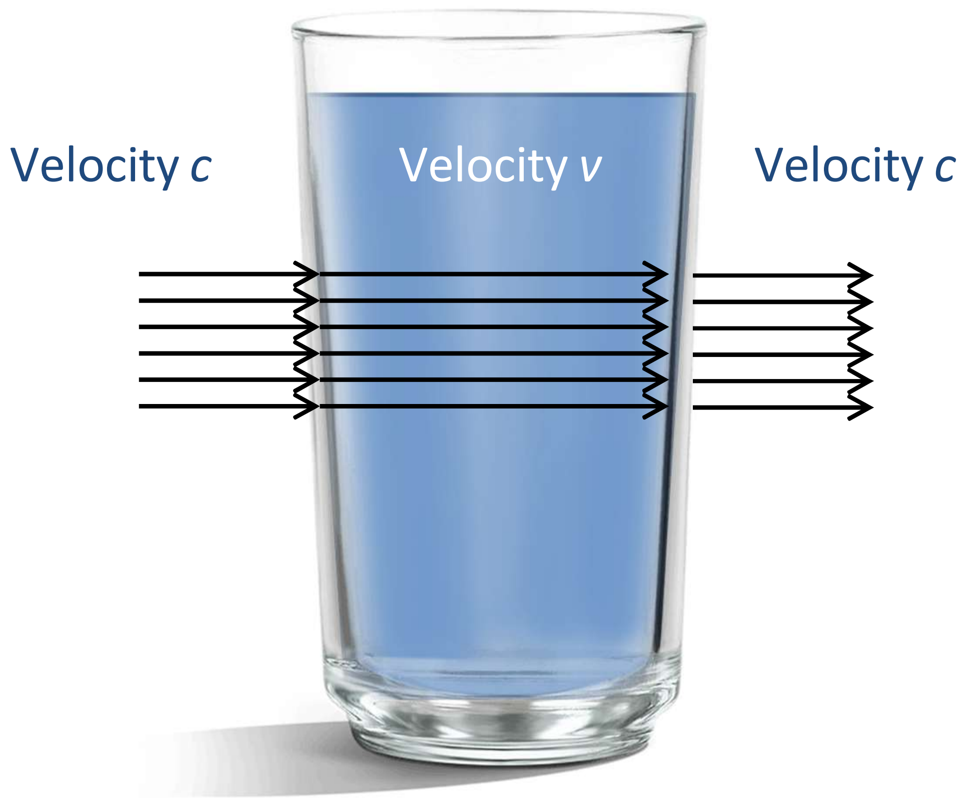


$$\text{Refractive Index} = \frac{!"\#\$}{!"\#\%}$$

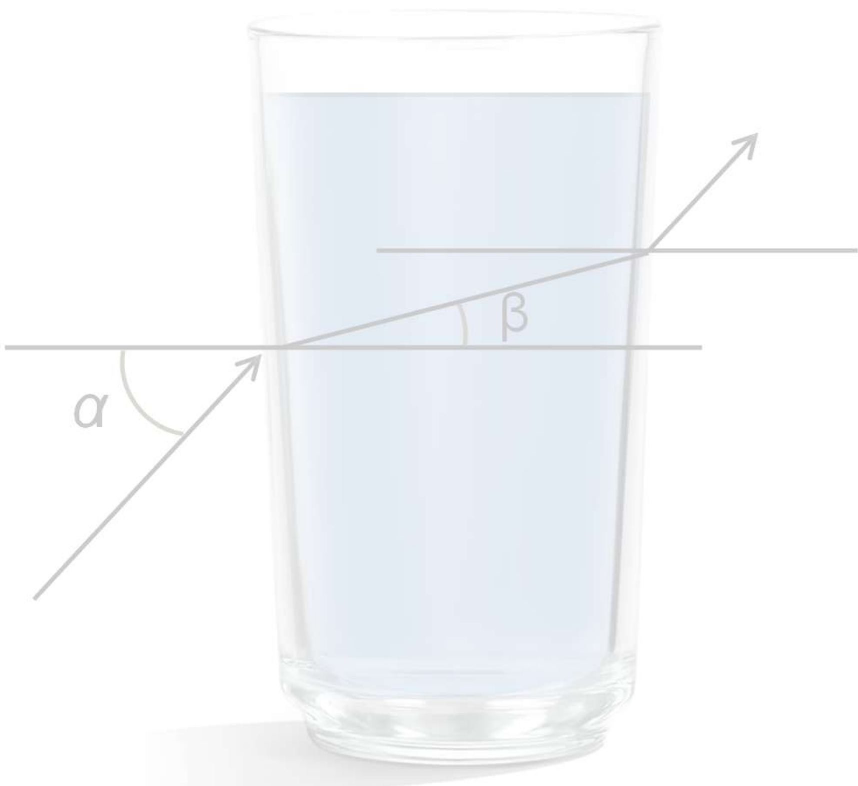


Refractive Index = !"#$ / !"#% = & / '

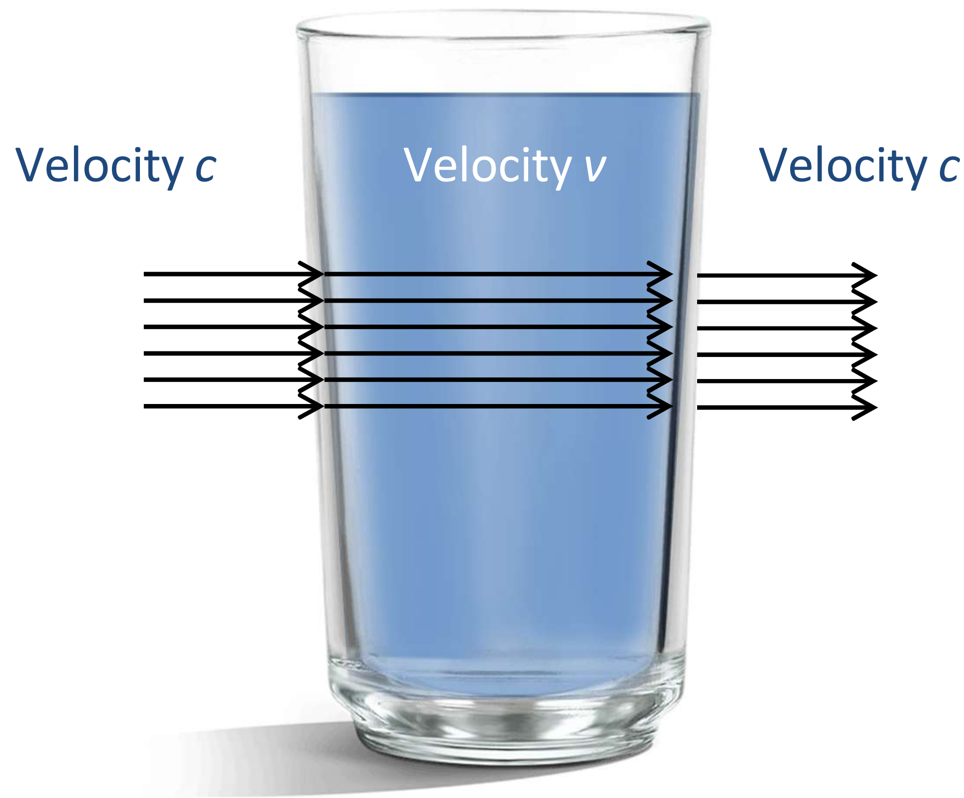




Refractive Index = !"#$ / !"#% = & / '

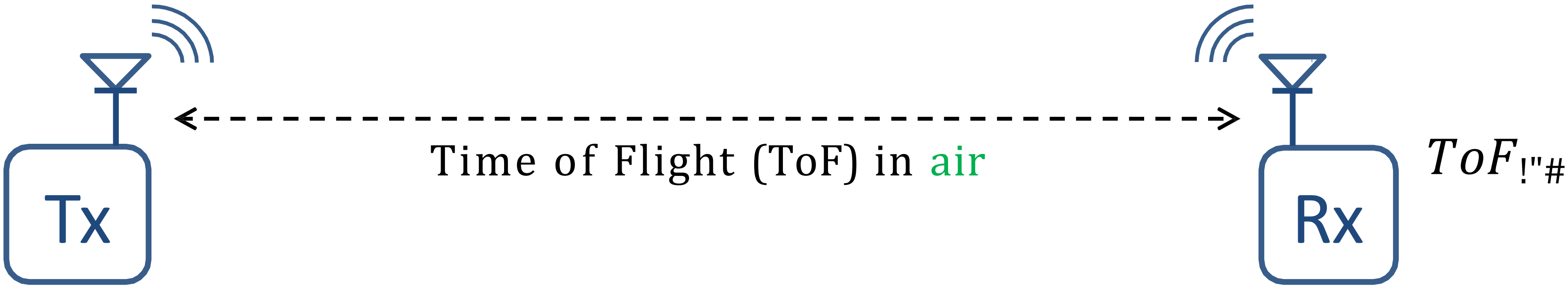


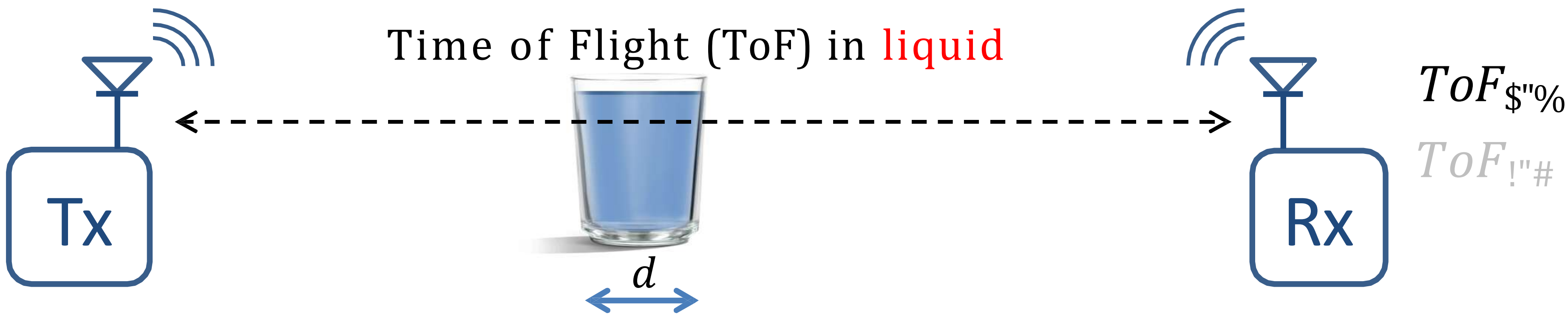
Measure “slow-down”

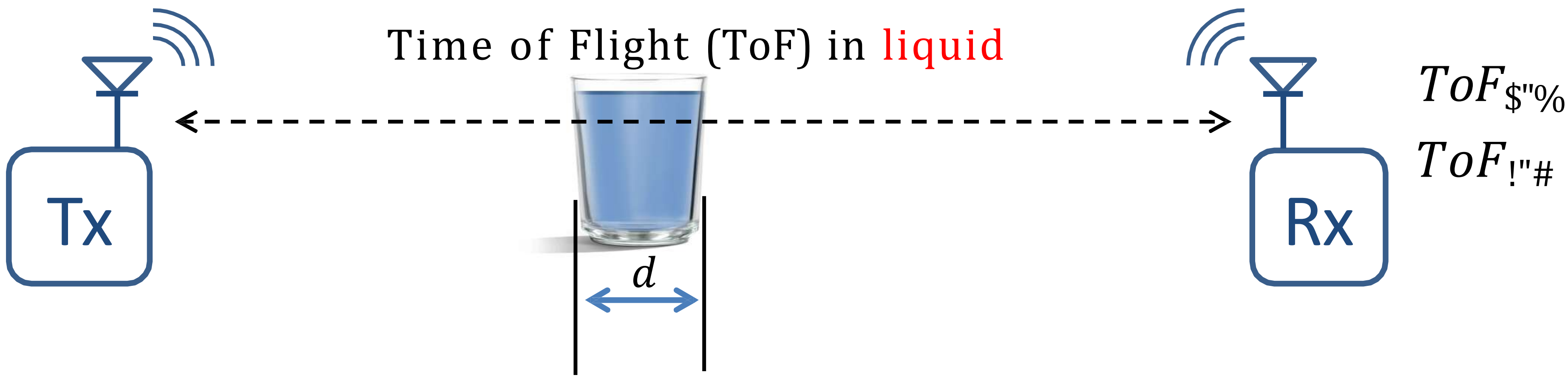


How to measure slow down ?

In principle, this is simple …

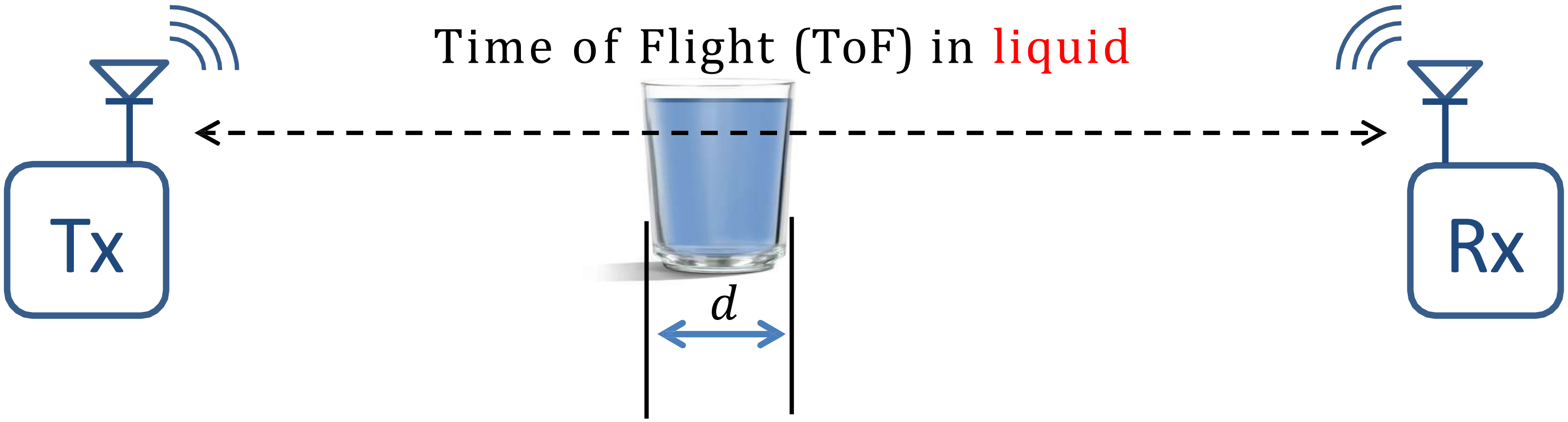

Tx
Time of Flight (ToF) in air
Rx
ToF!"#


Time of Flight (ToF) in liquid
Tx
Rx
d
ToF$"%
ToF!"#



$$ToF_{()*} - ToF_{+),} = \frac{d}{v} - \frac{d}{c}$$

Time of Flight (ToF) in liquid



$$ToF_{()^{*}} - ToF_{+),} = \frac{d}{v} - \frac{d}{c}$$

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

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So how can we measure these 2 ToFs?

$$ToF_{()*} - ToF_{+),} = \frac{d}{v} - \frac{d}{c}$$

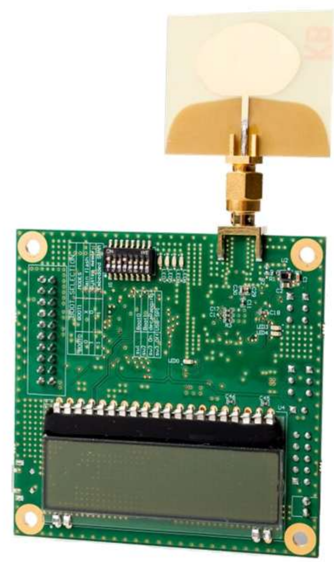
$$Refractive\ Index = \frac{c}{v}$$

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

$$ToF_{()*} - ToF_{+),} = \frac{d}{v} - \frac{d}{c}$$

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

Is nanosecond good enough ?

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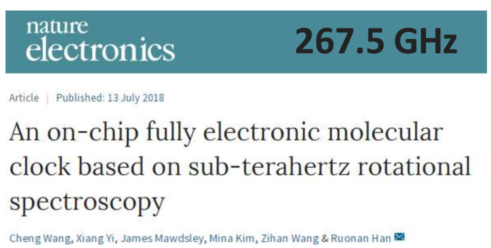
Is nanosecond good enough ?

–

≈



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

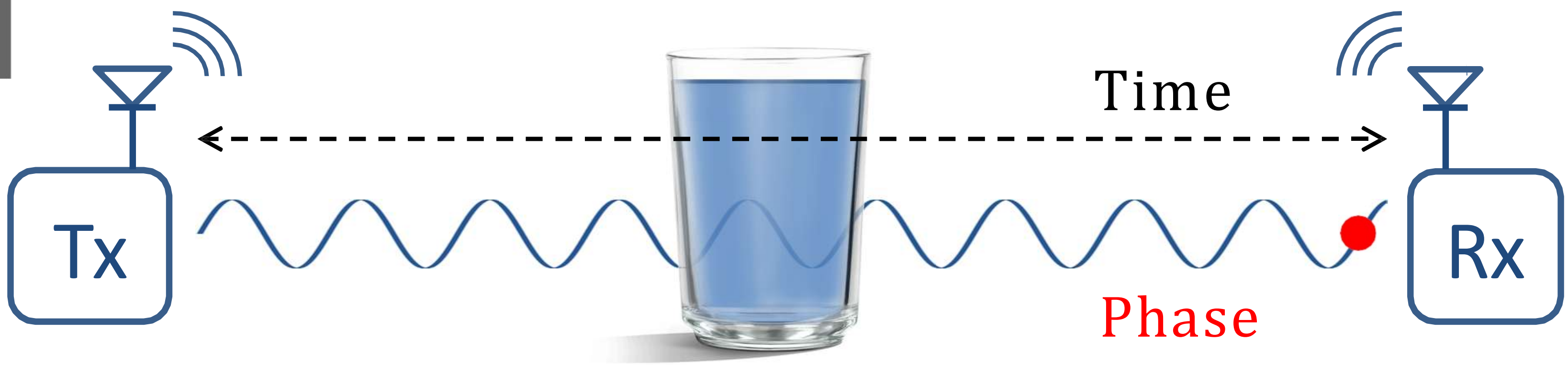
–

≈ **1 nanosec.**

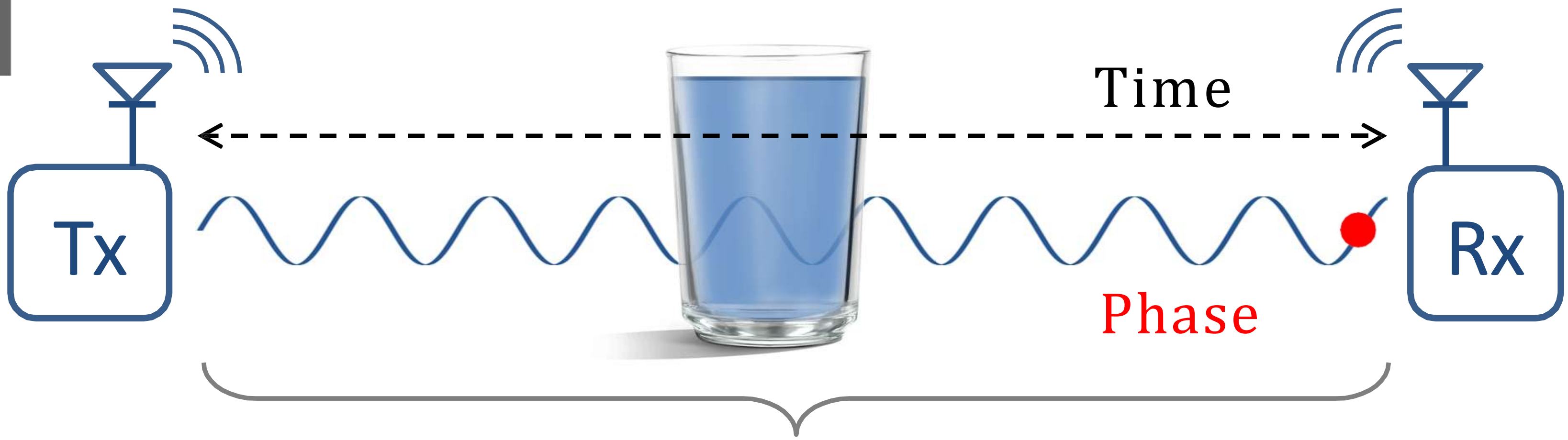
Absolute ToF difficult at picoseconds

Nanosec. gives coarse grained estimate … useful but not sufficient

Phase

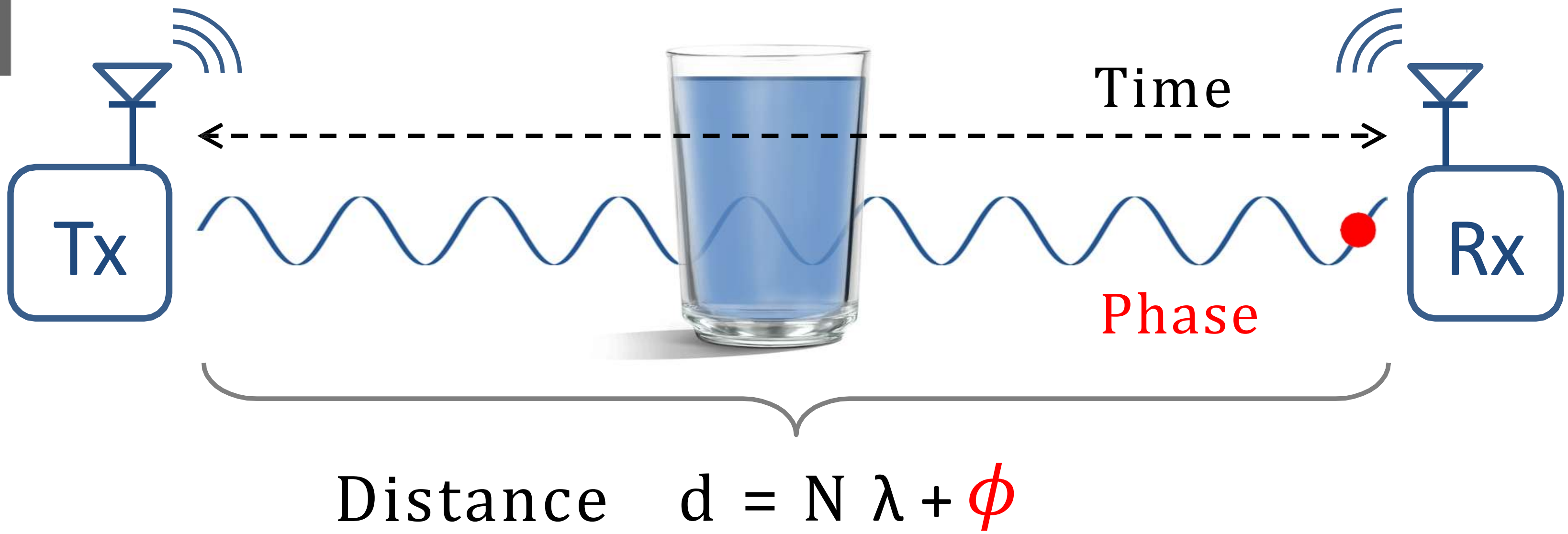


Phase



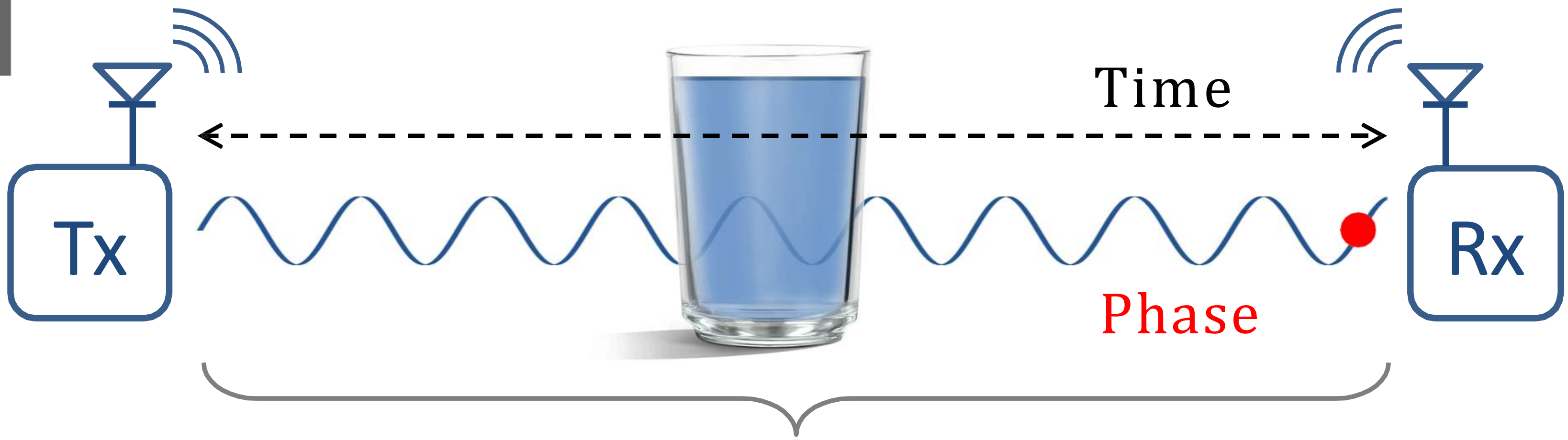
Distance $d = N\lambda + \phi$

Phase



and ϕ measurable in very high resolution …

Phase



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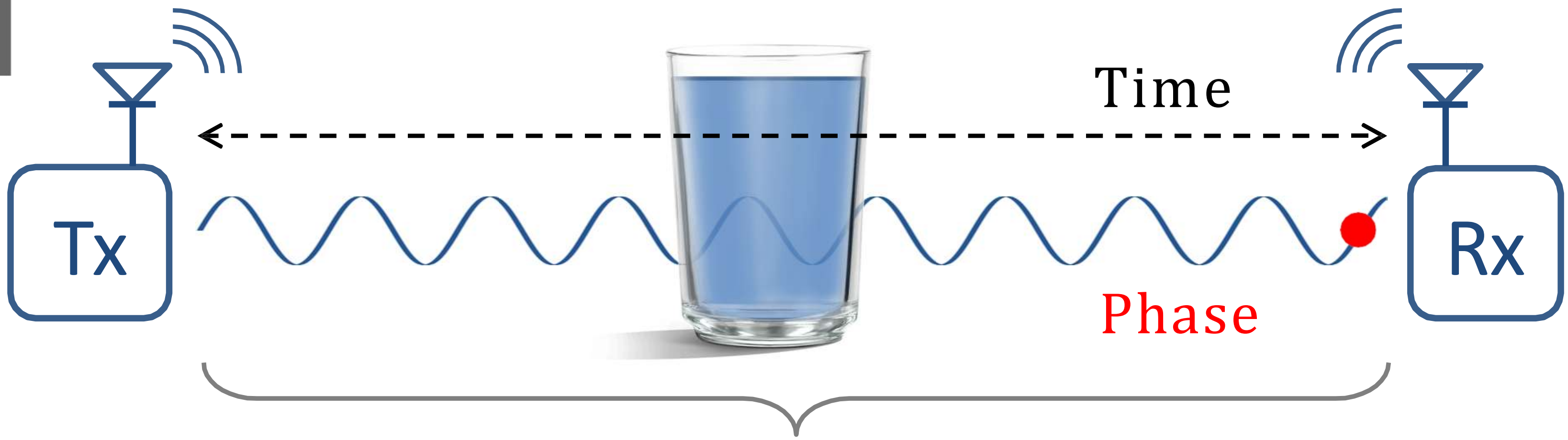
and ϕ measurable in very high resolution …

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

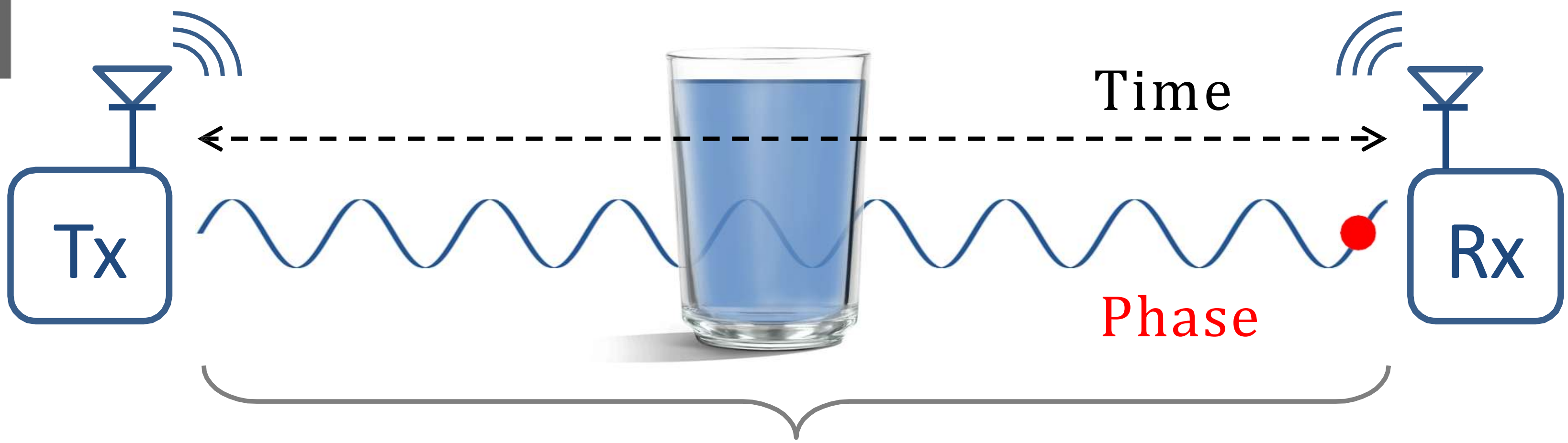
Phase



$$d = N\lambda + \phi$$

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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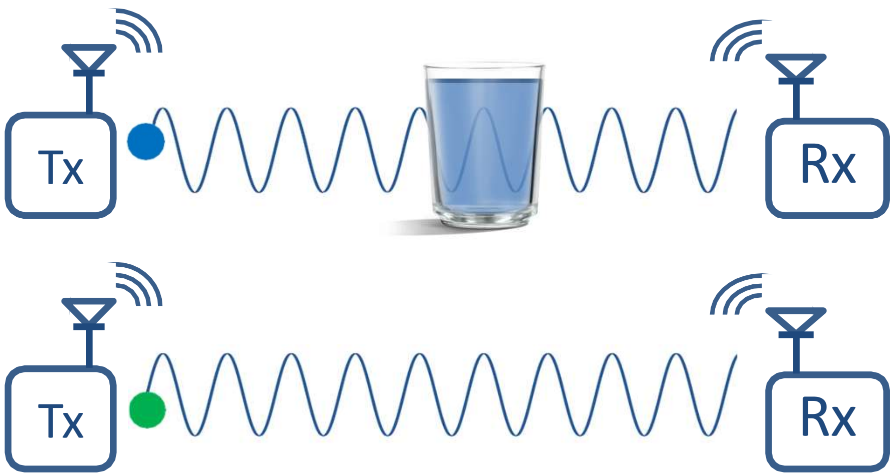
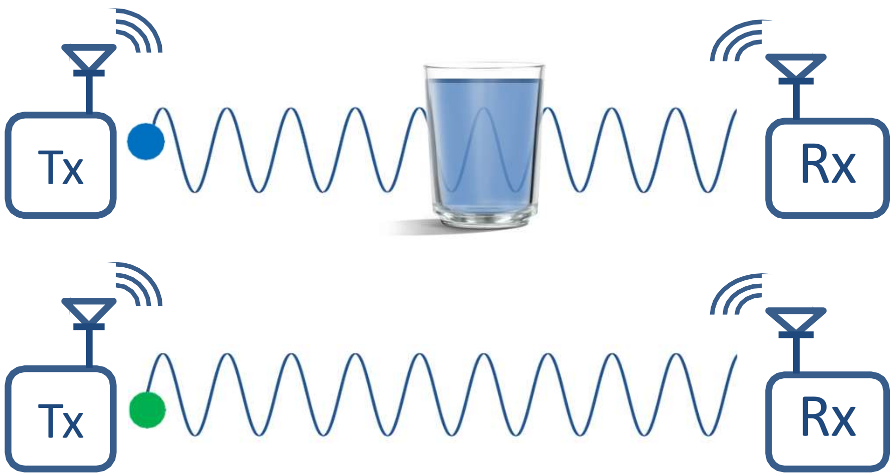


N is unknown

✓ Possible to solve by combining with time (ToF)

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



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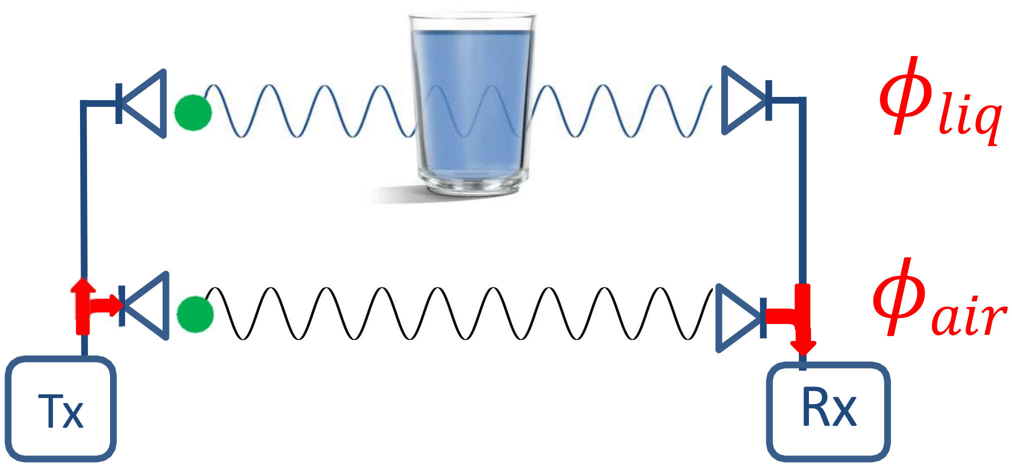
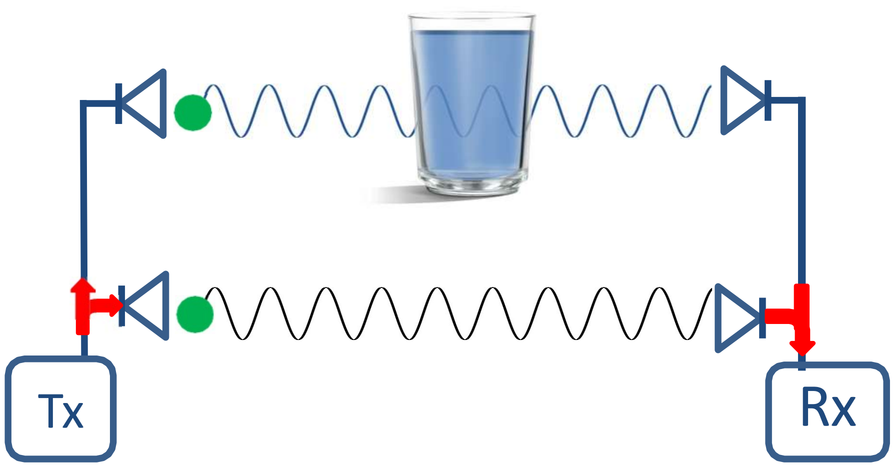


But we only care about relative phases = $\phi_{liq} - \phi_{air}$

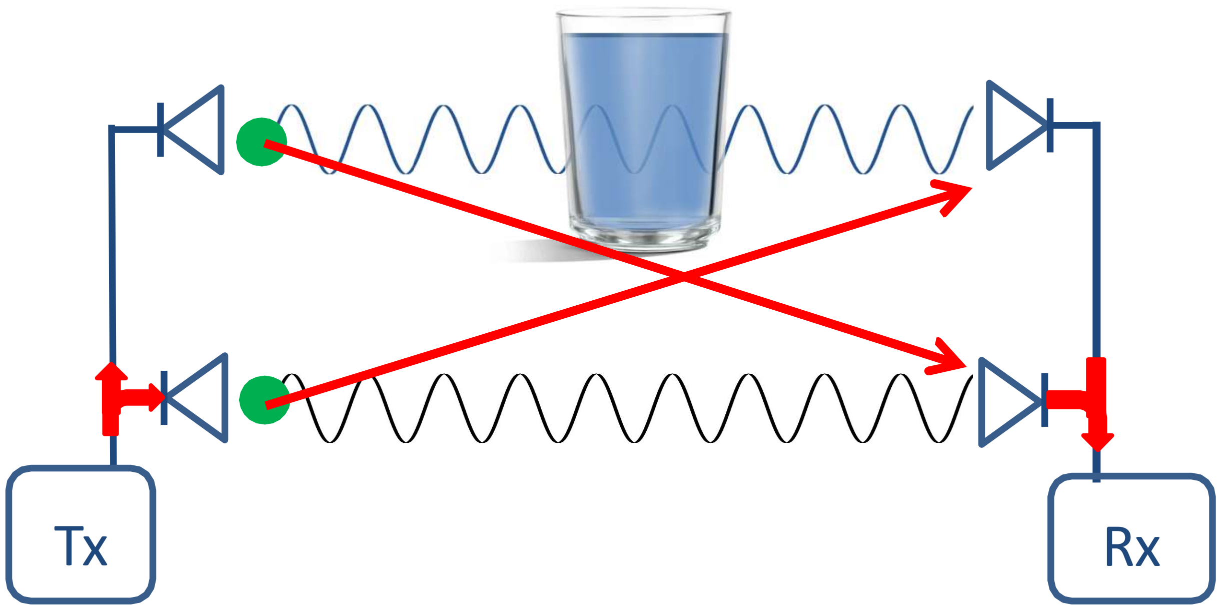
So, we create a parallel (***atomic)*** measurement …

And cancel the initial phase by subtraction



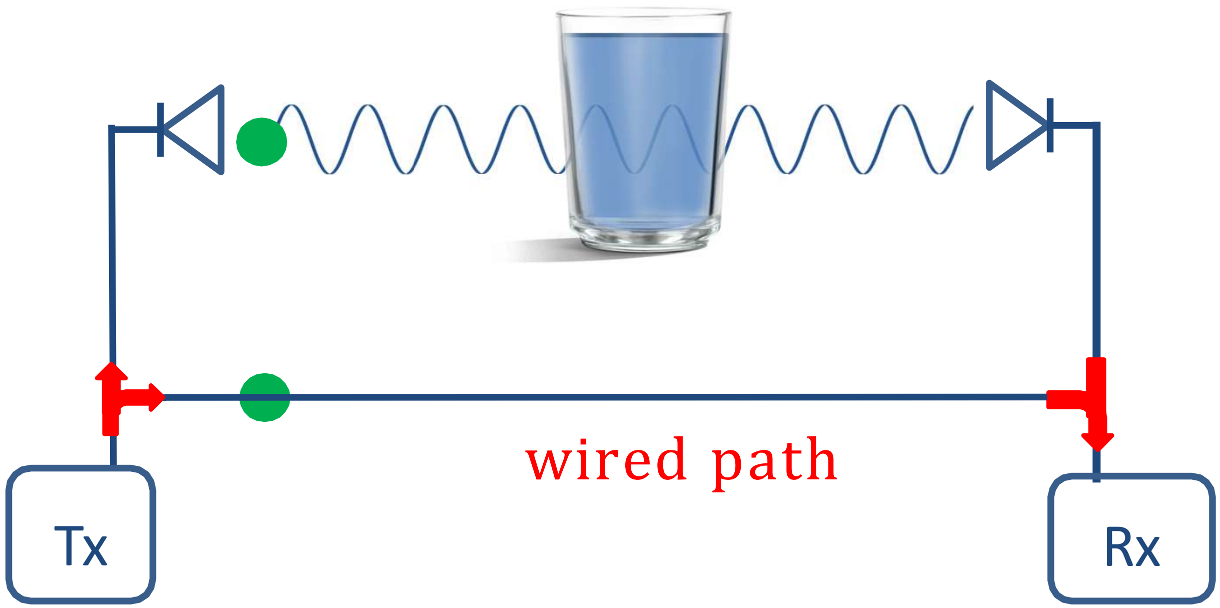
$\phi_{liq} - \phi_{air}$

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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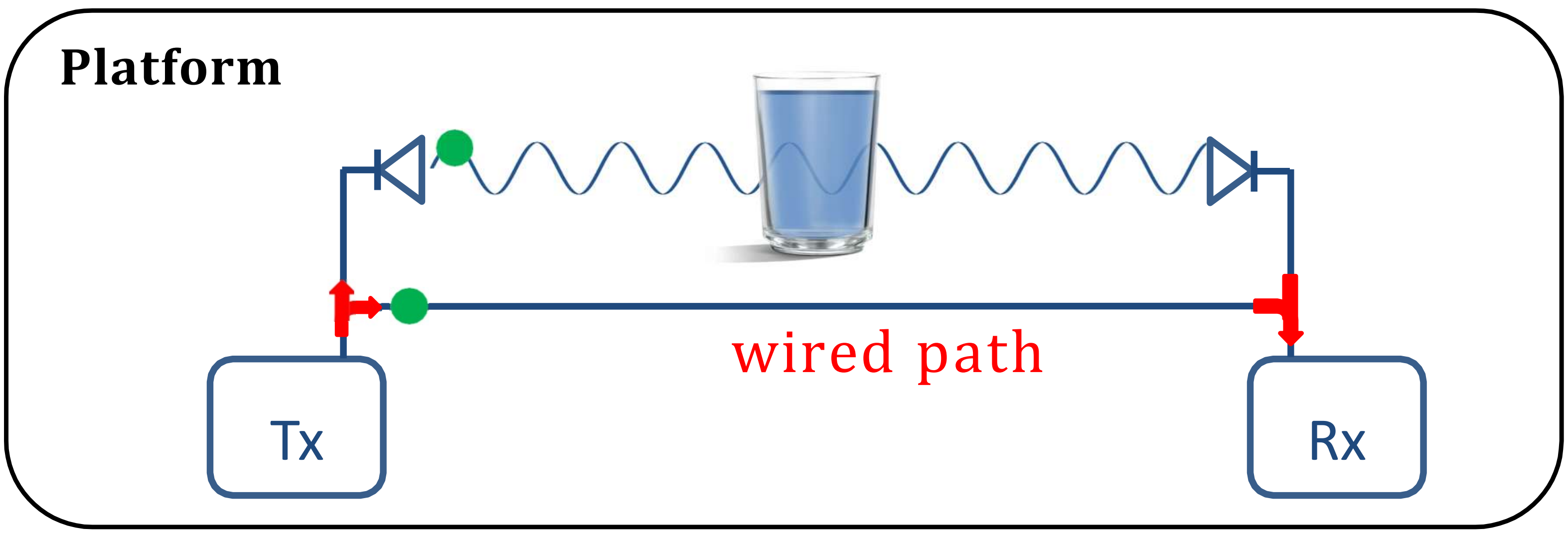


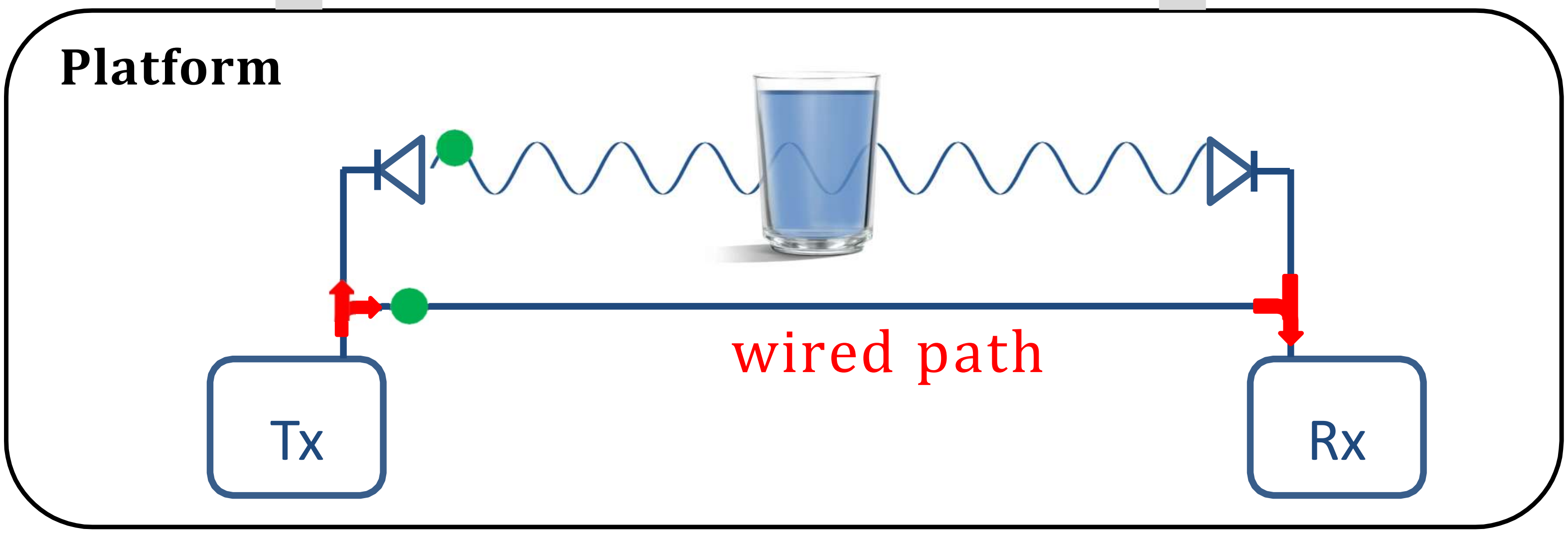
Summarizing what we have thus far…

Nanoseconds

$$ToF_{!"\#} - ToF_{\$"\%\&} = \Delta T^{!"\#}_{\$"\%\&}$$

Picoseconds

$$\phi_{liq} - \phi_{wire} = \Delta\phi^{\%'\&}_{!"\#\$}$$



Fuse time + phase ➔ Refractive index

Nanoseconds

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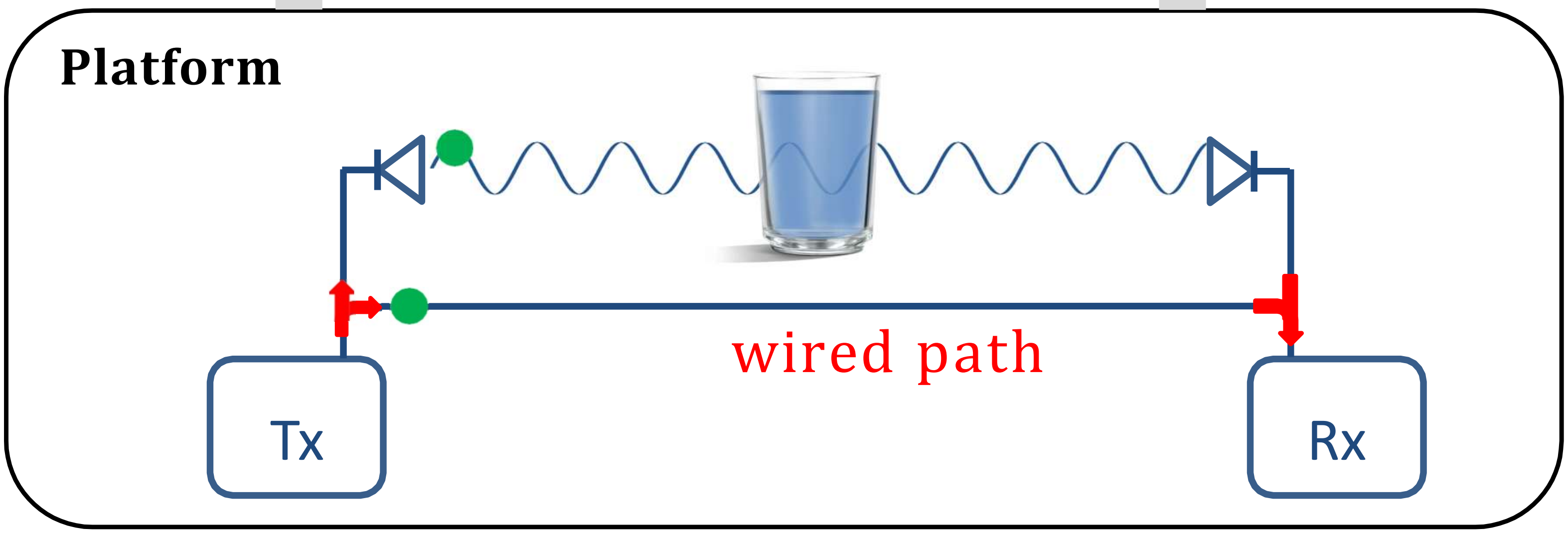
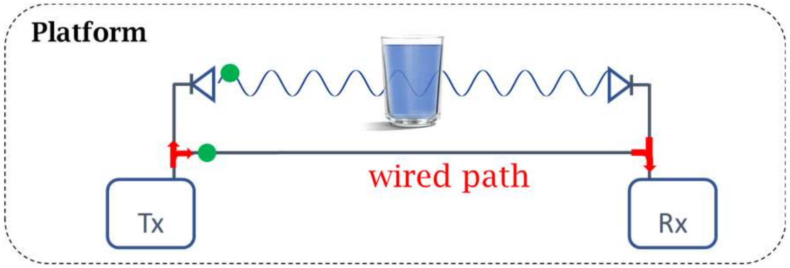


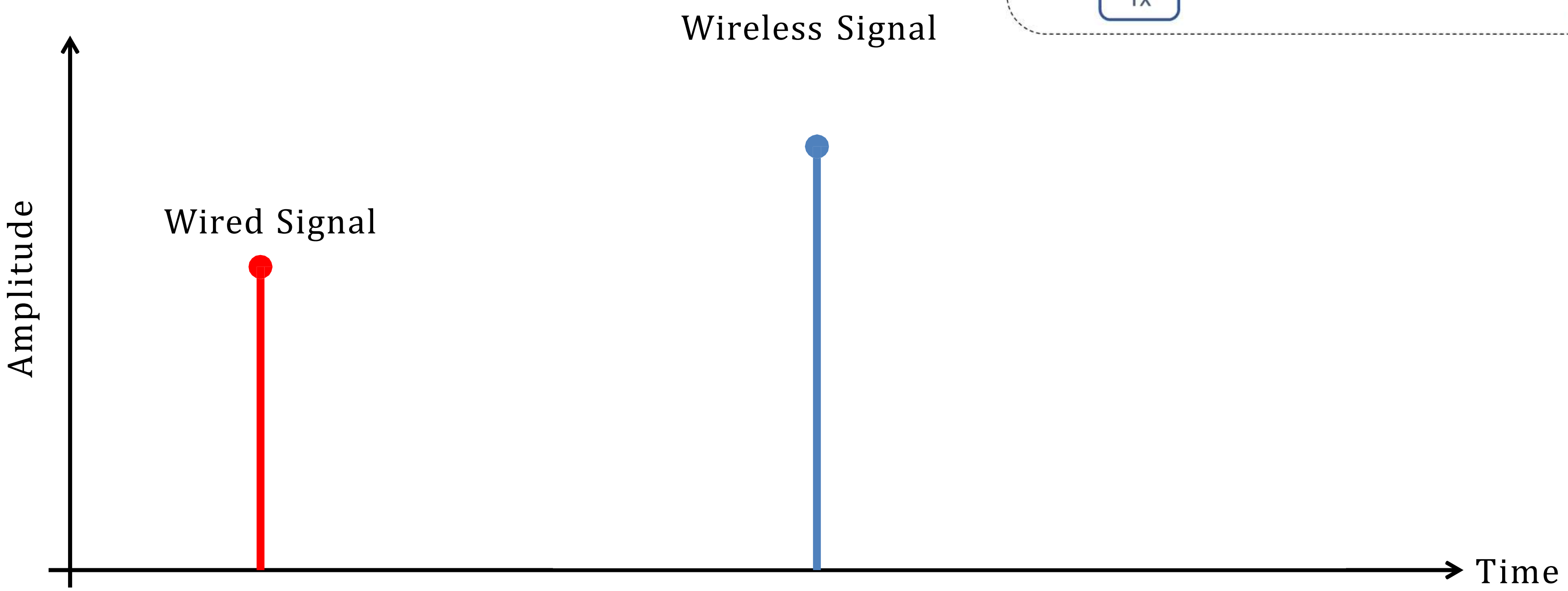
We have an idealized sketch of the solution …

Let's now turn to practice …

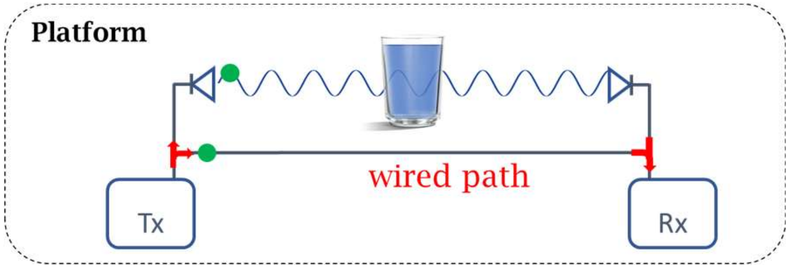
with real radios and environments

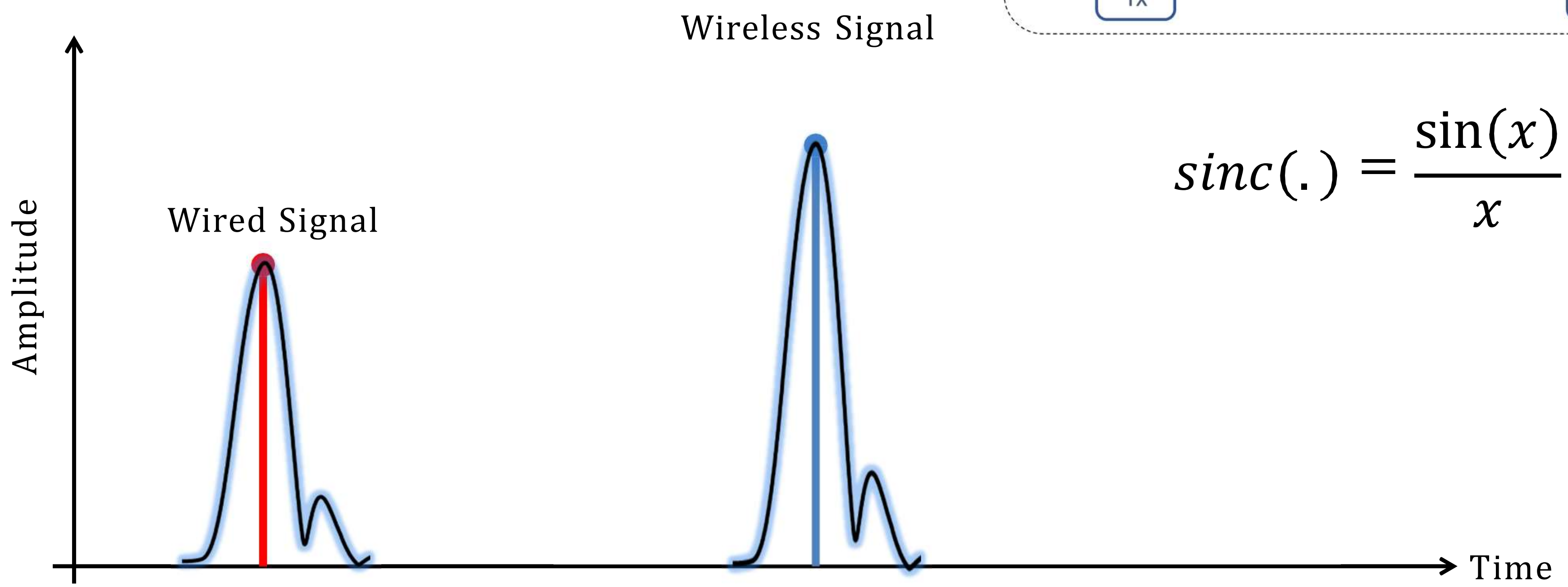
Ideally, at the Receiver…





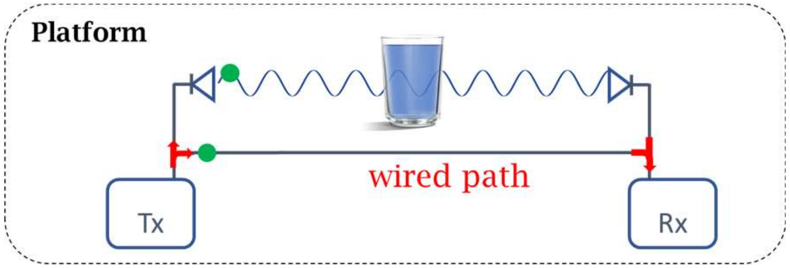
Practical Hardware causes Distortions

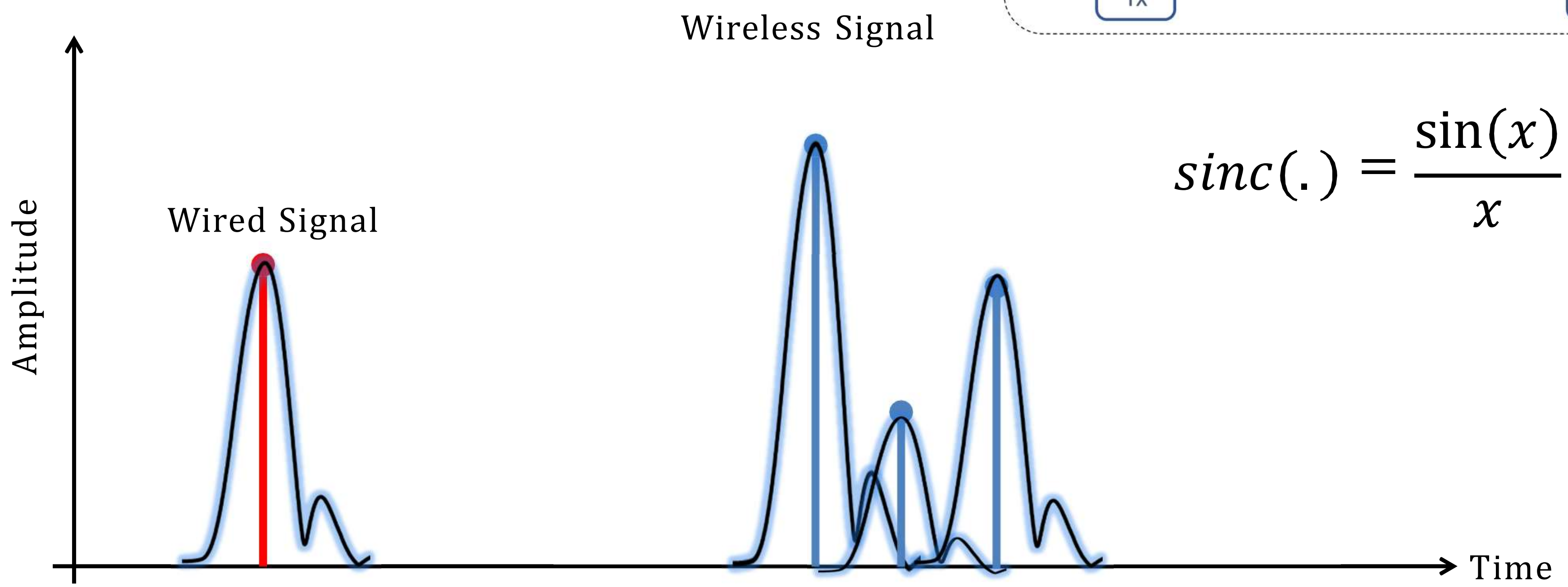




$$sinc(.) = \frac{\sin(x)}{x}$$

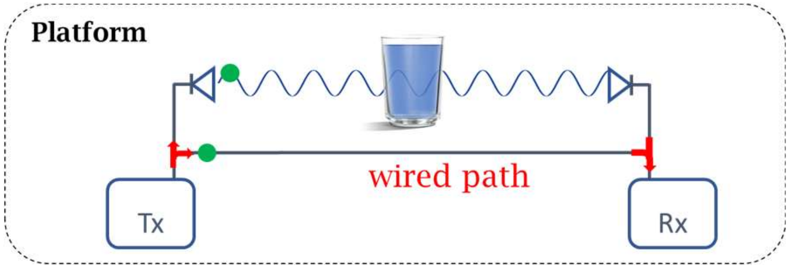
Multipath causes more Distortions

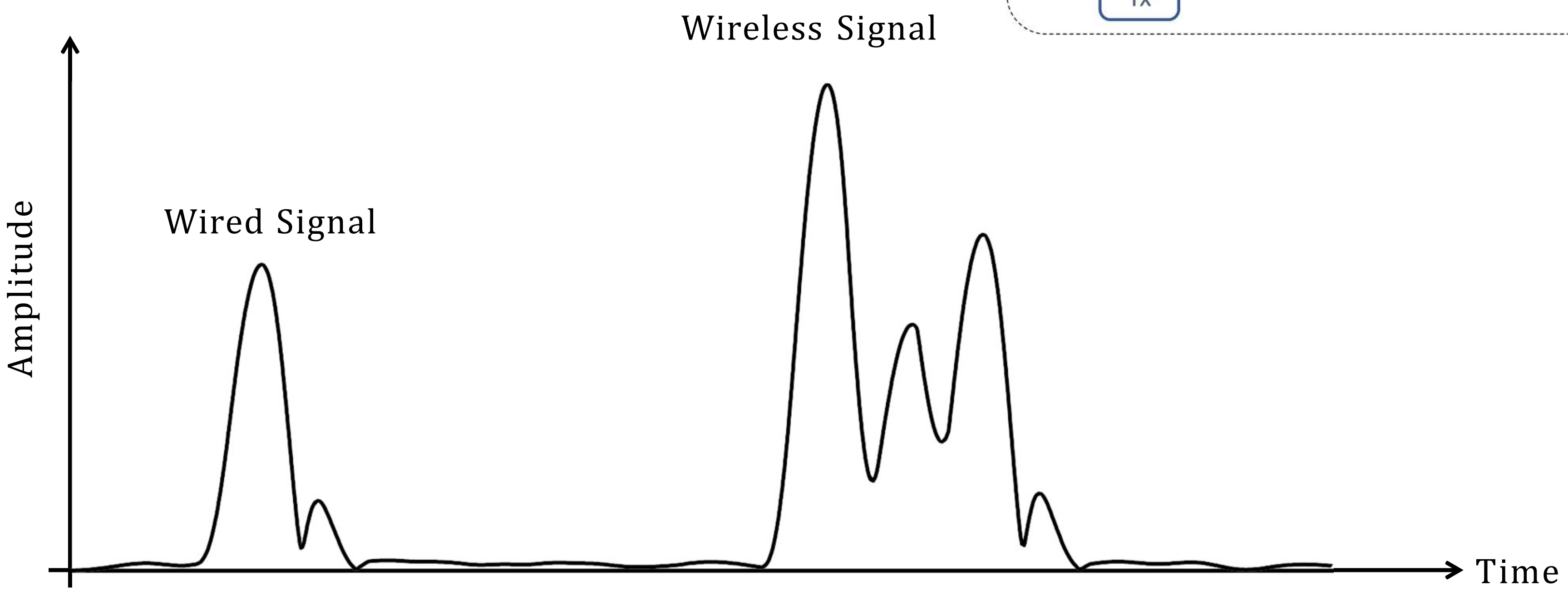




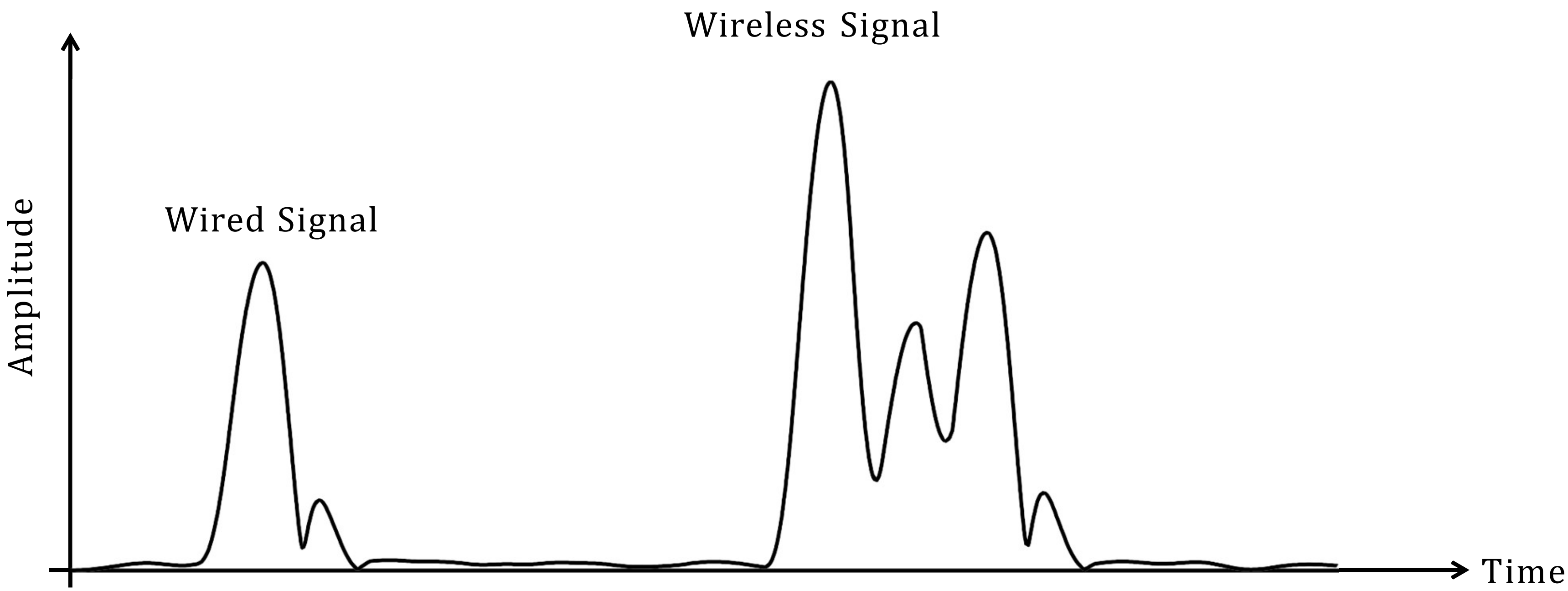
$$sinc(.) = \frac{\sin(x)}{x}$$

This is the received signal at Rx





Main question: Where are the wired, wireless impulses?



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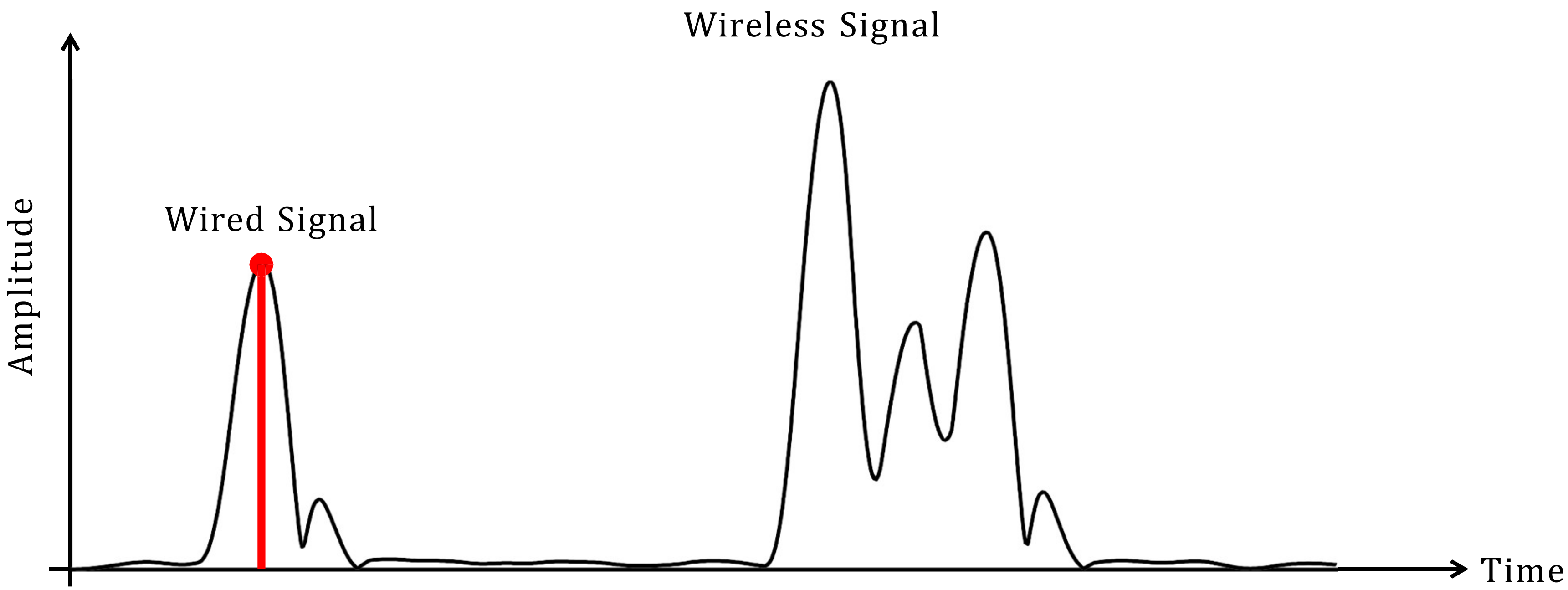

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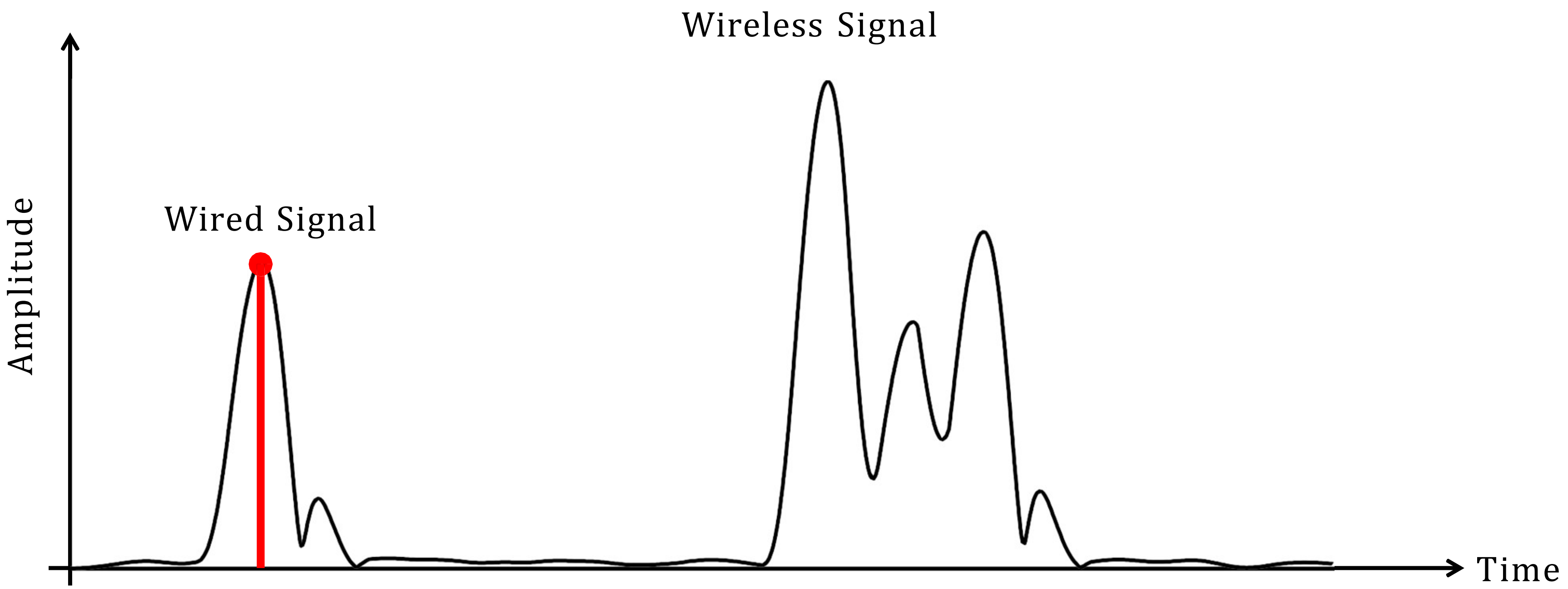

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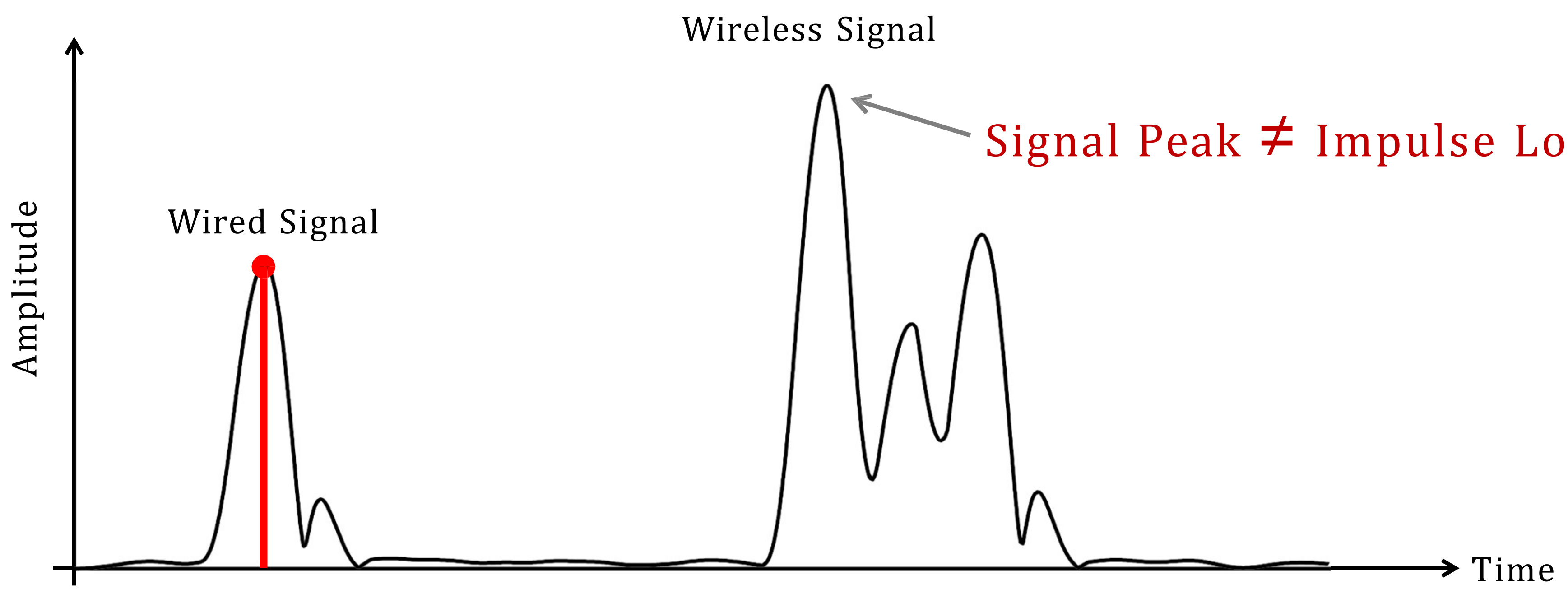

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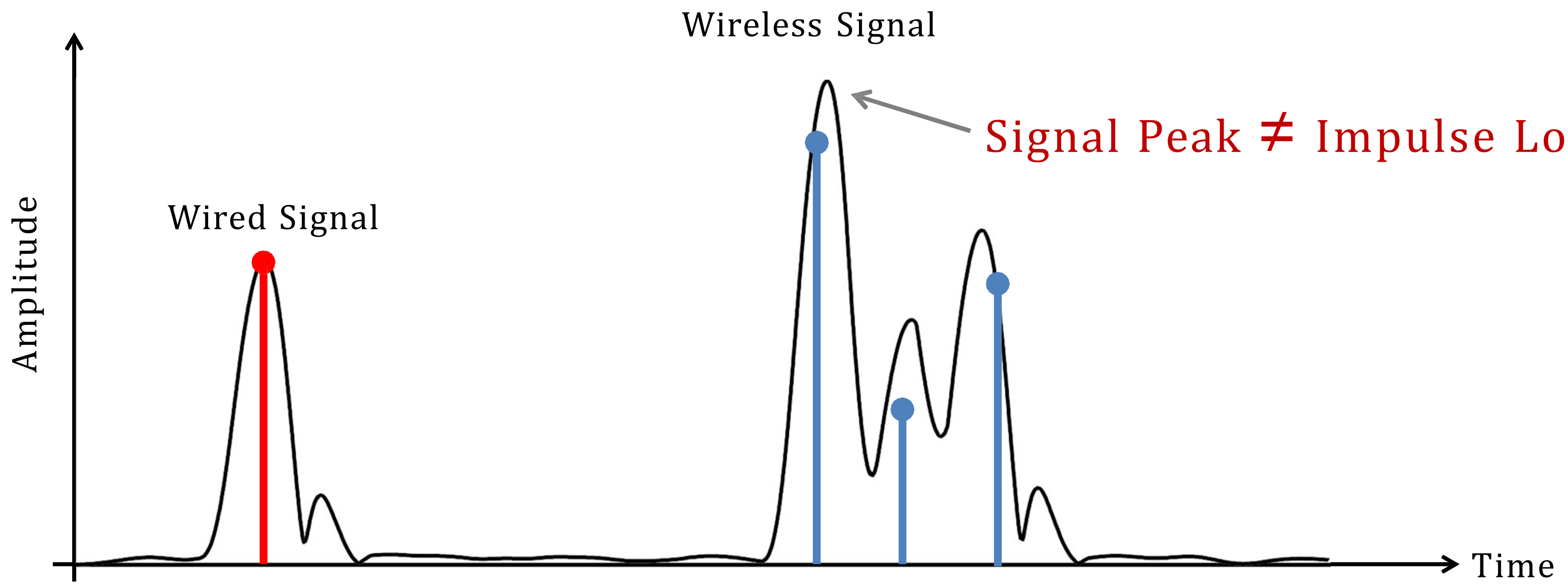

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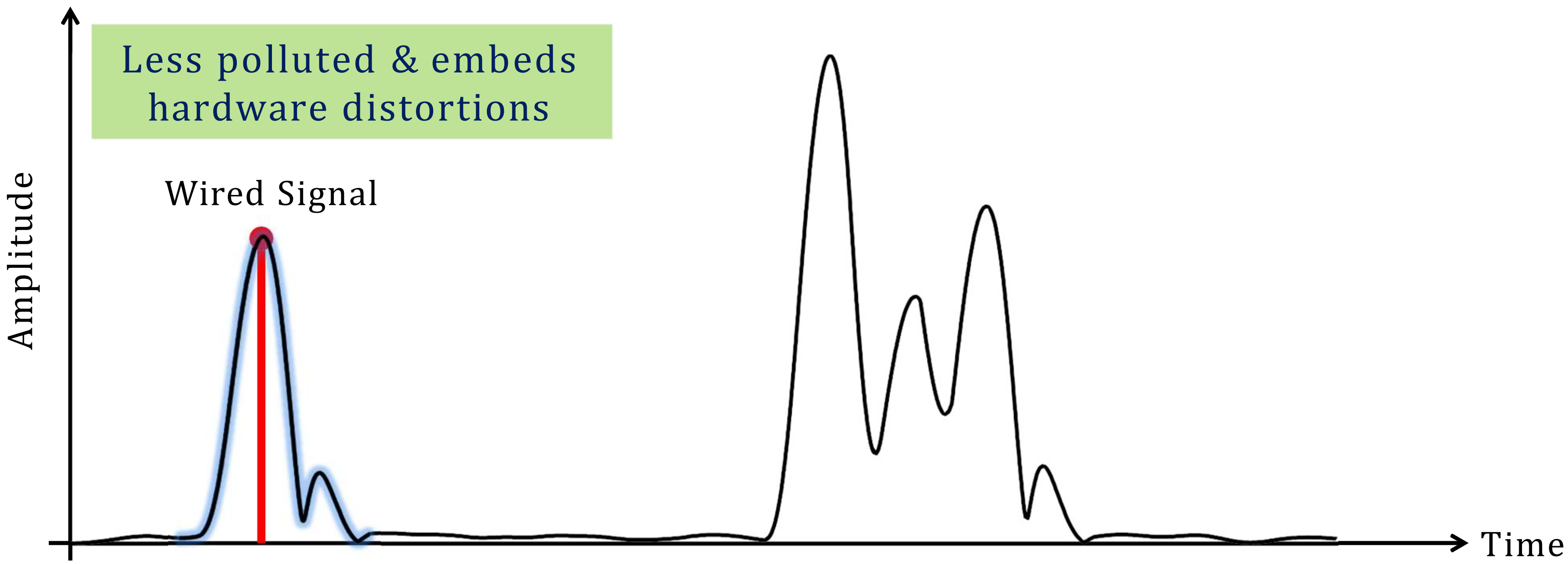
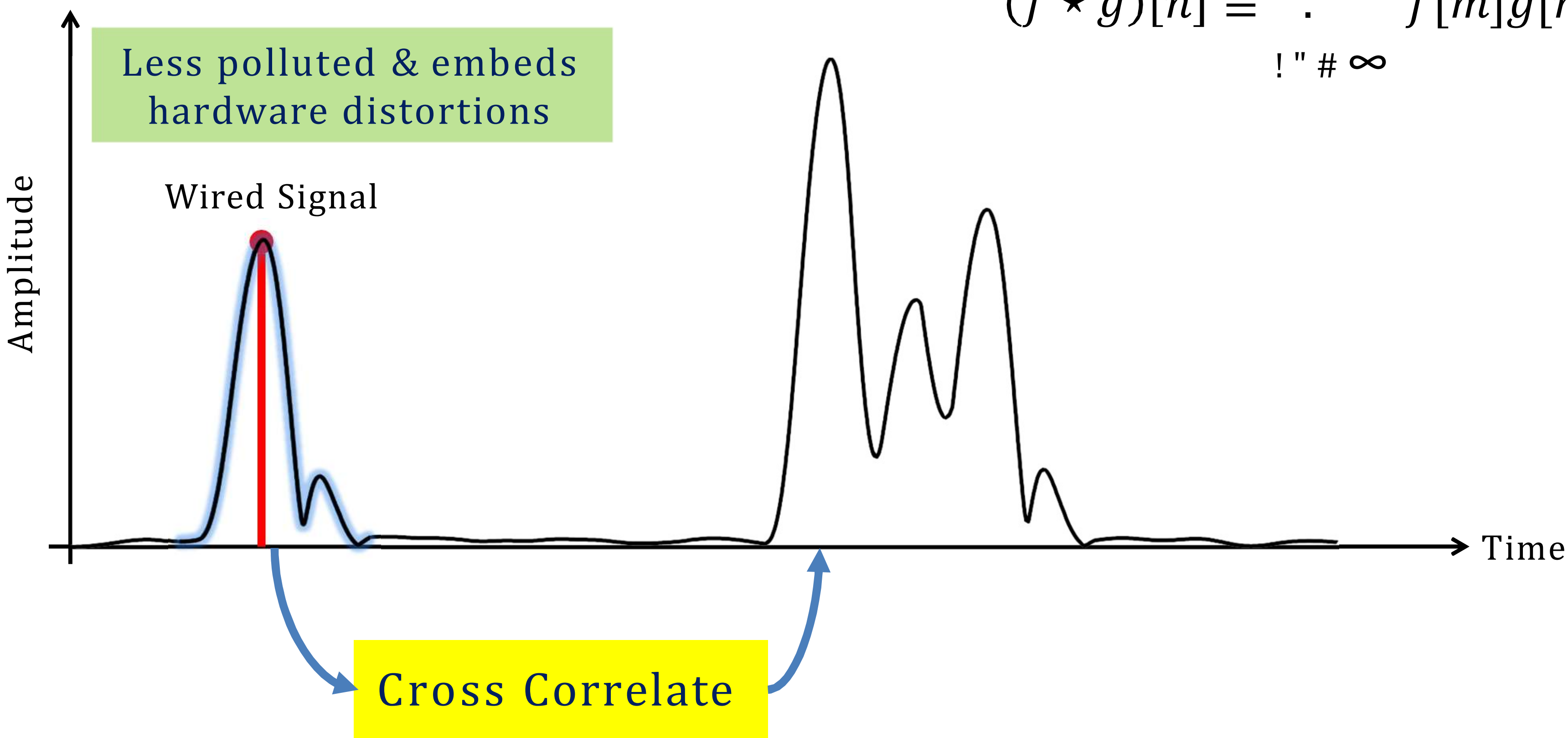
Template Matching



Template Matching

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



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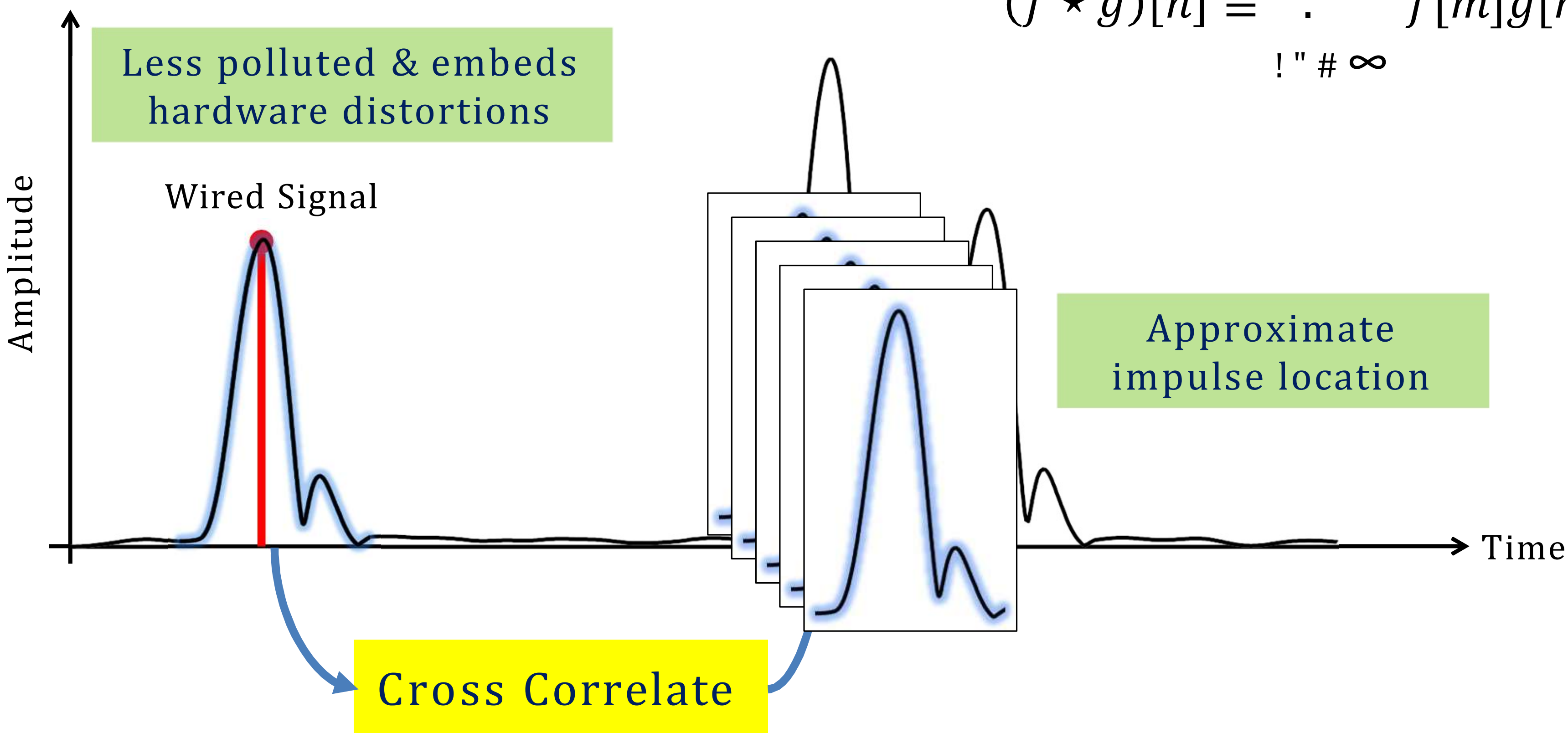
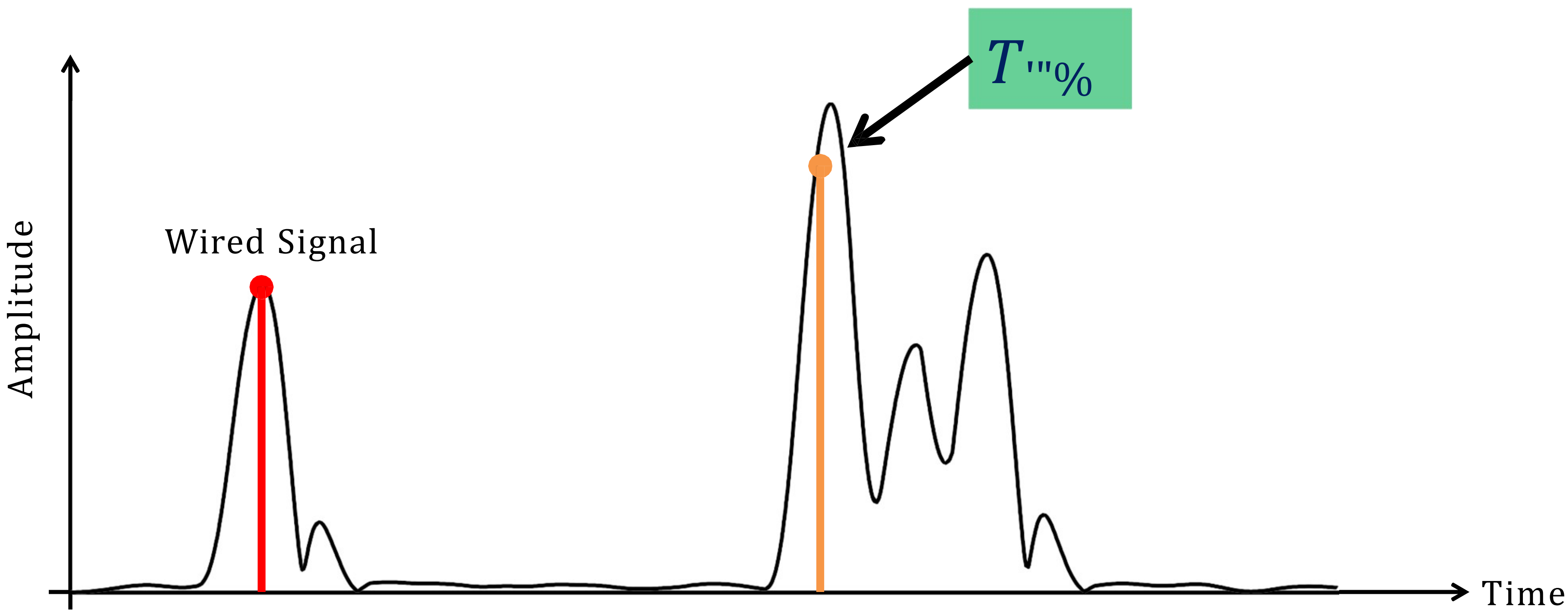
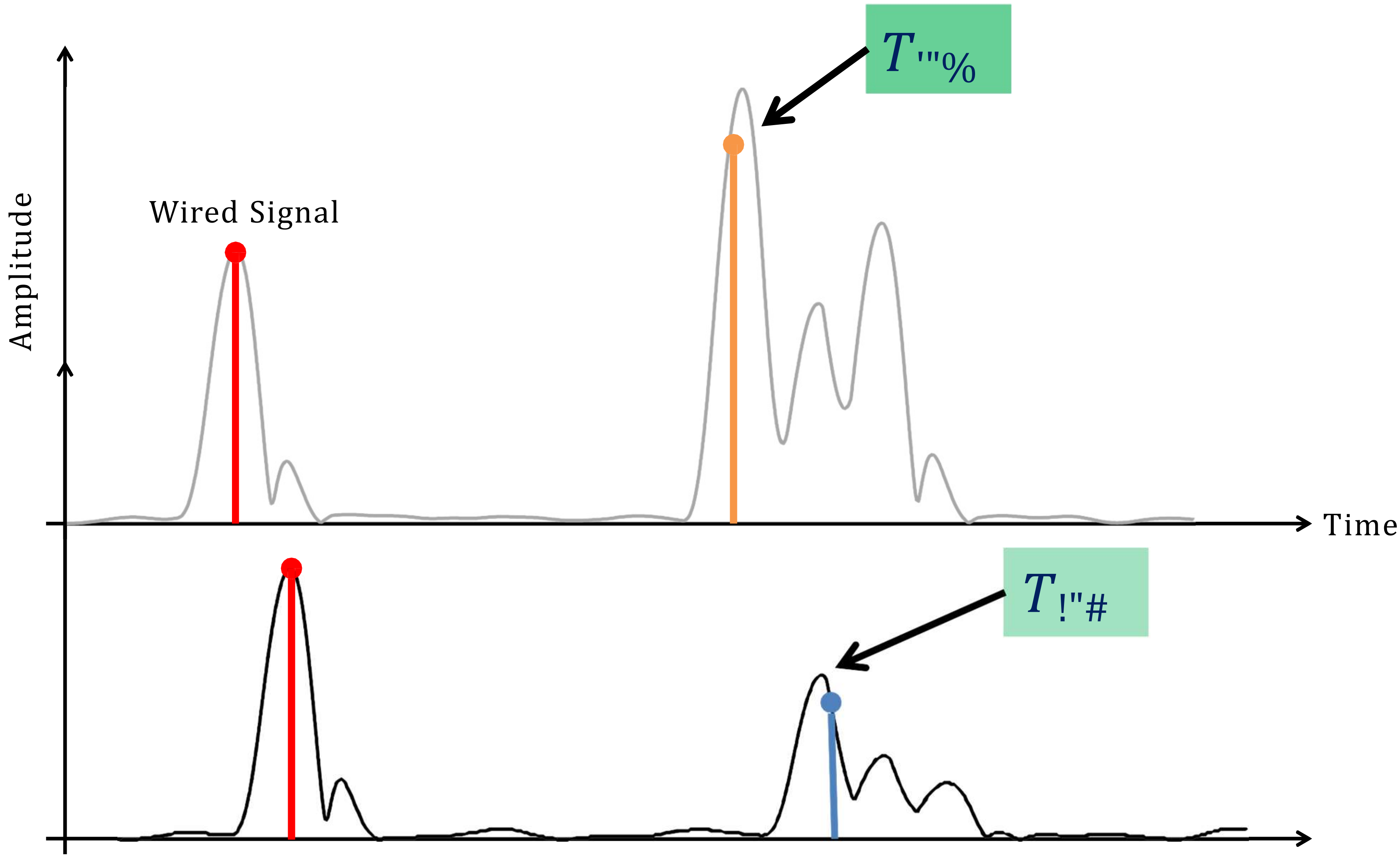
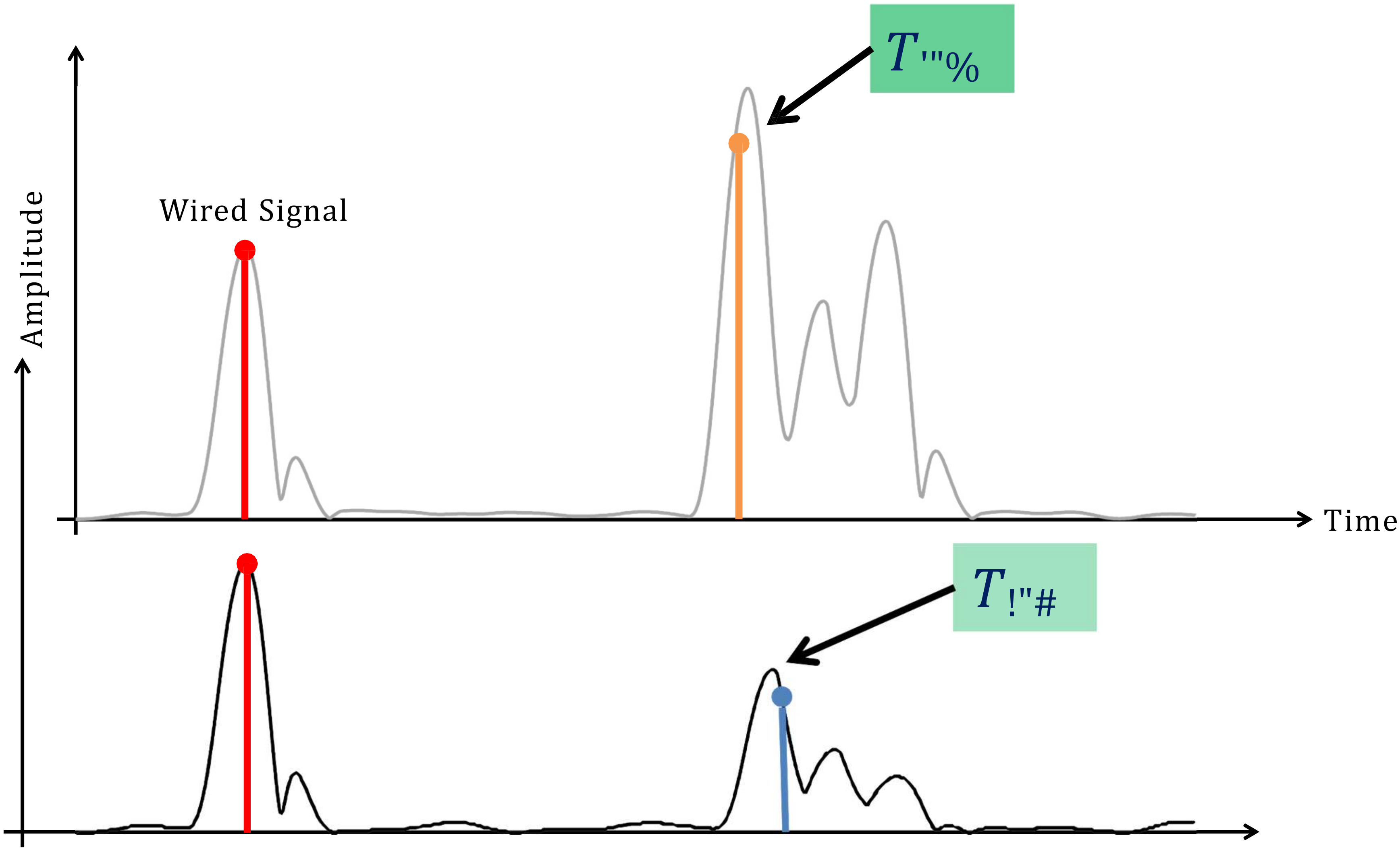


Correct Time Value for Air





Amplitude
Wired Signal
T '"%
T !"#
Time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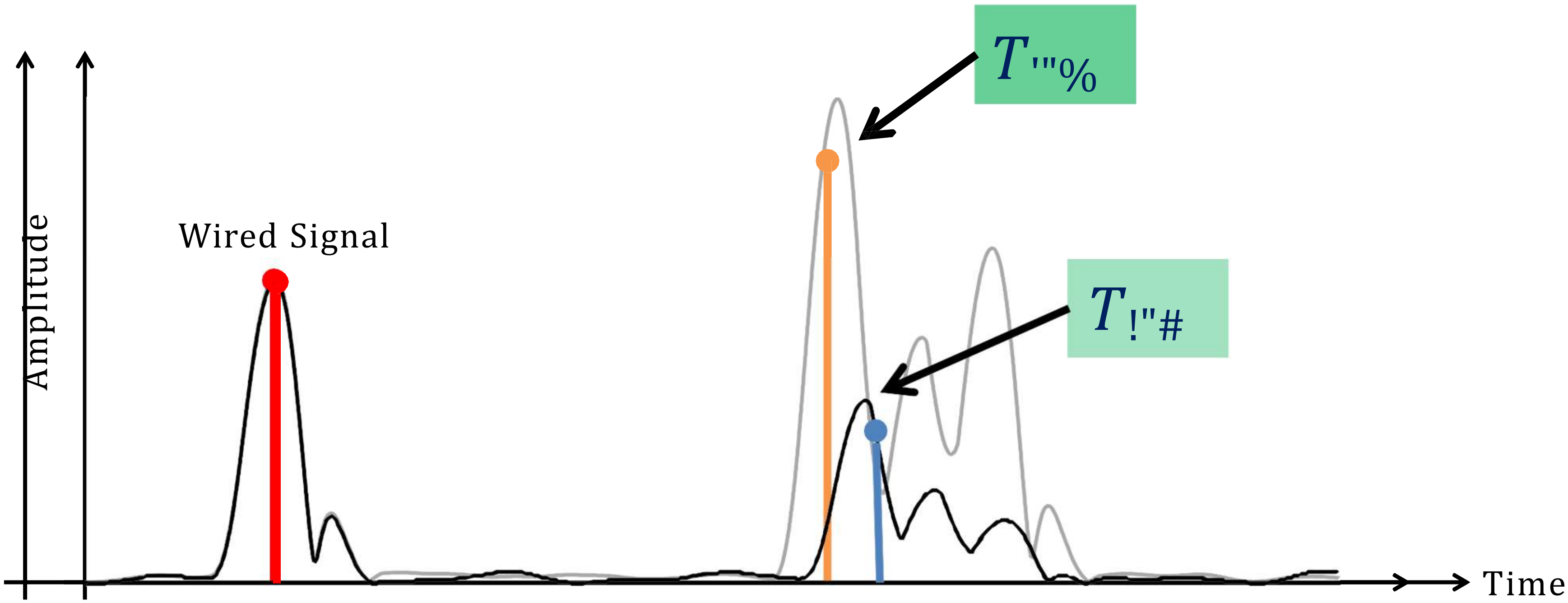
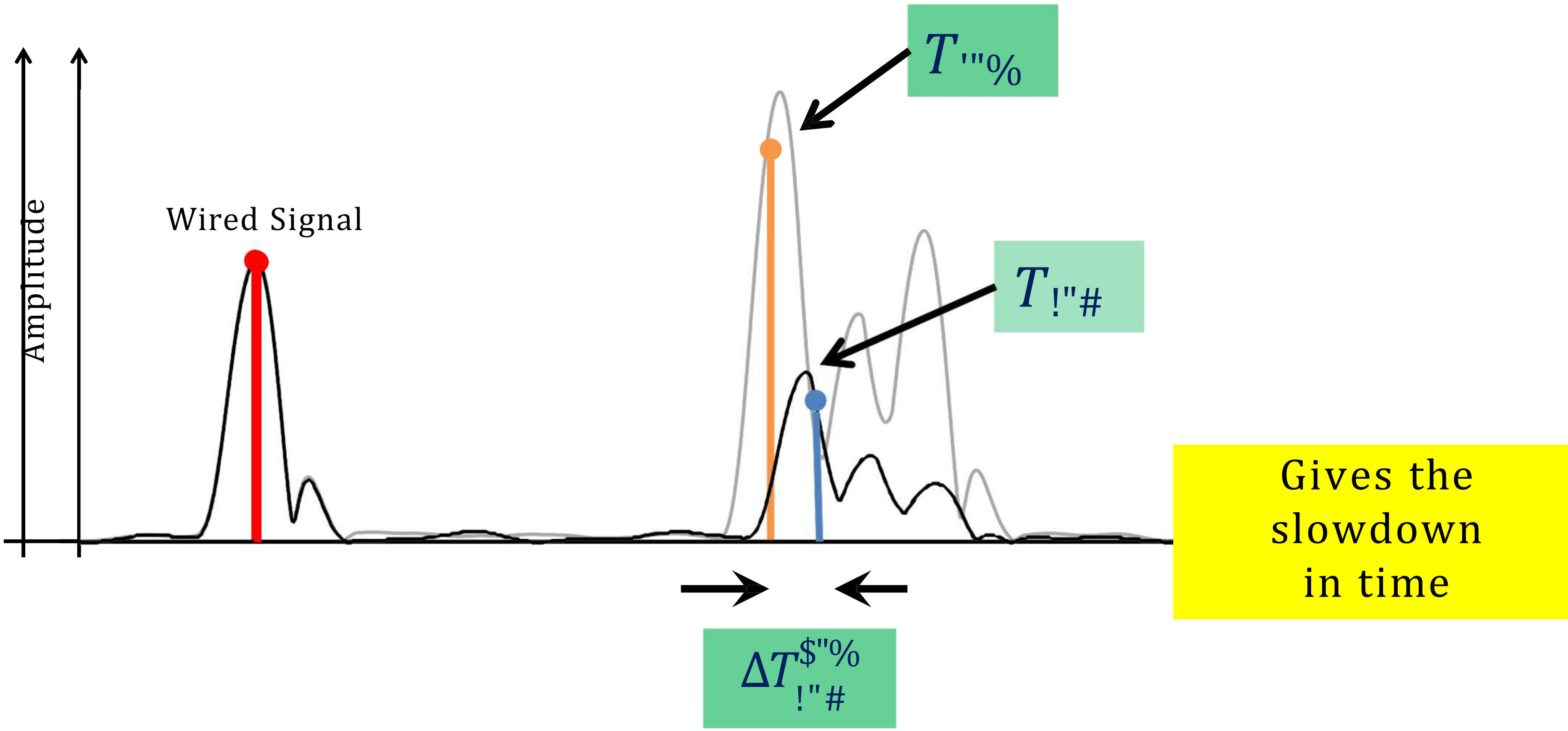
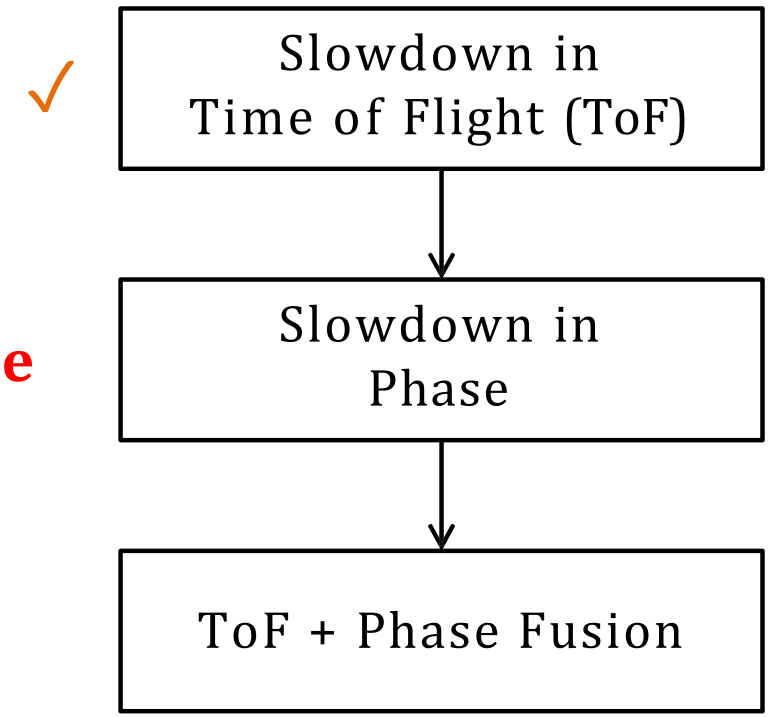

T'"%
T!"#
Wired Signal
Amplitude
Time



$$\Delta T^{!"\#}_{'''\%} = \left(T_{!"\#} - T_{\$"\%\&}\right) - \left(T_{'''\%} - T_{\$"\%\&}\right)$$

✓ Slowdown in
Time of Flight (ToF)

We now need slowdown in phase



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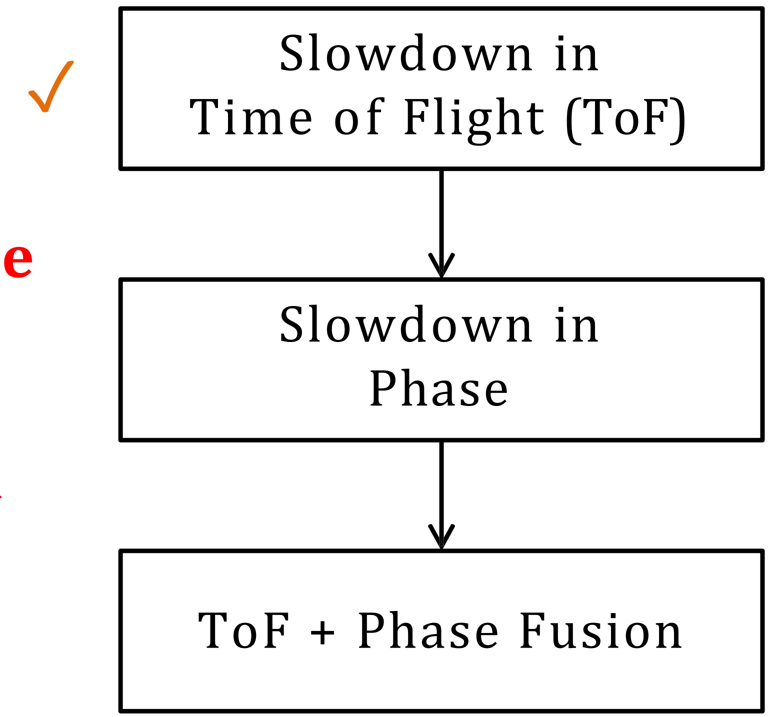
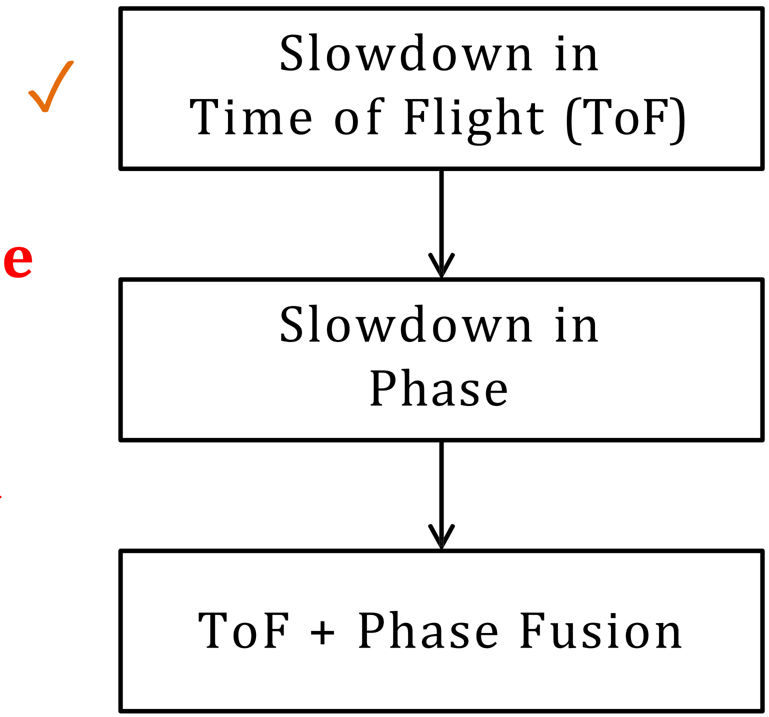
Key Opportunity:
Phase is stable and undistorted



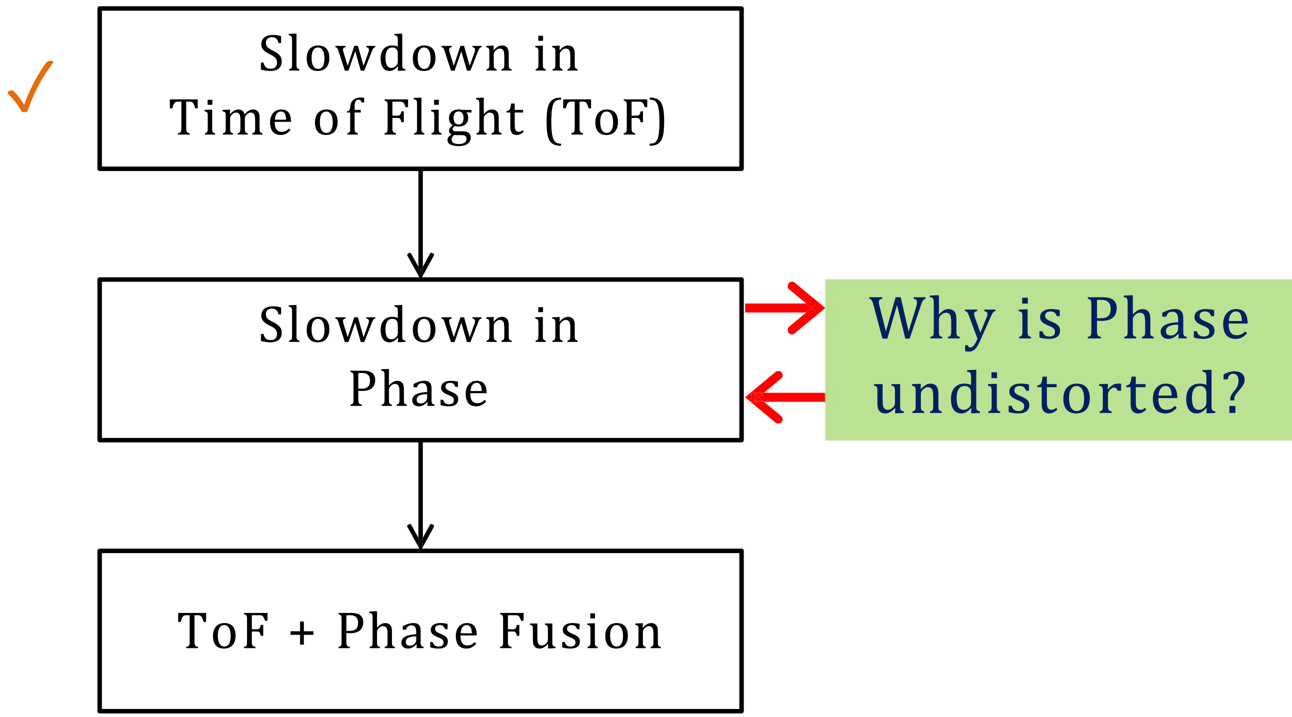
We now need slowdown in phase

Key Opportunity:
Phase is stable and undistorted

Why?

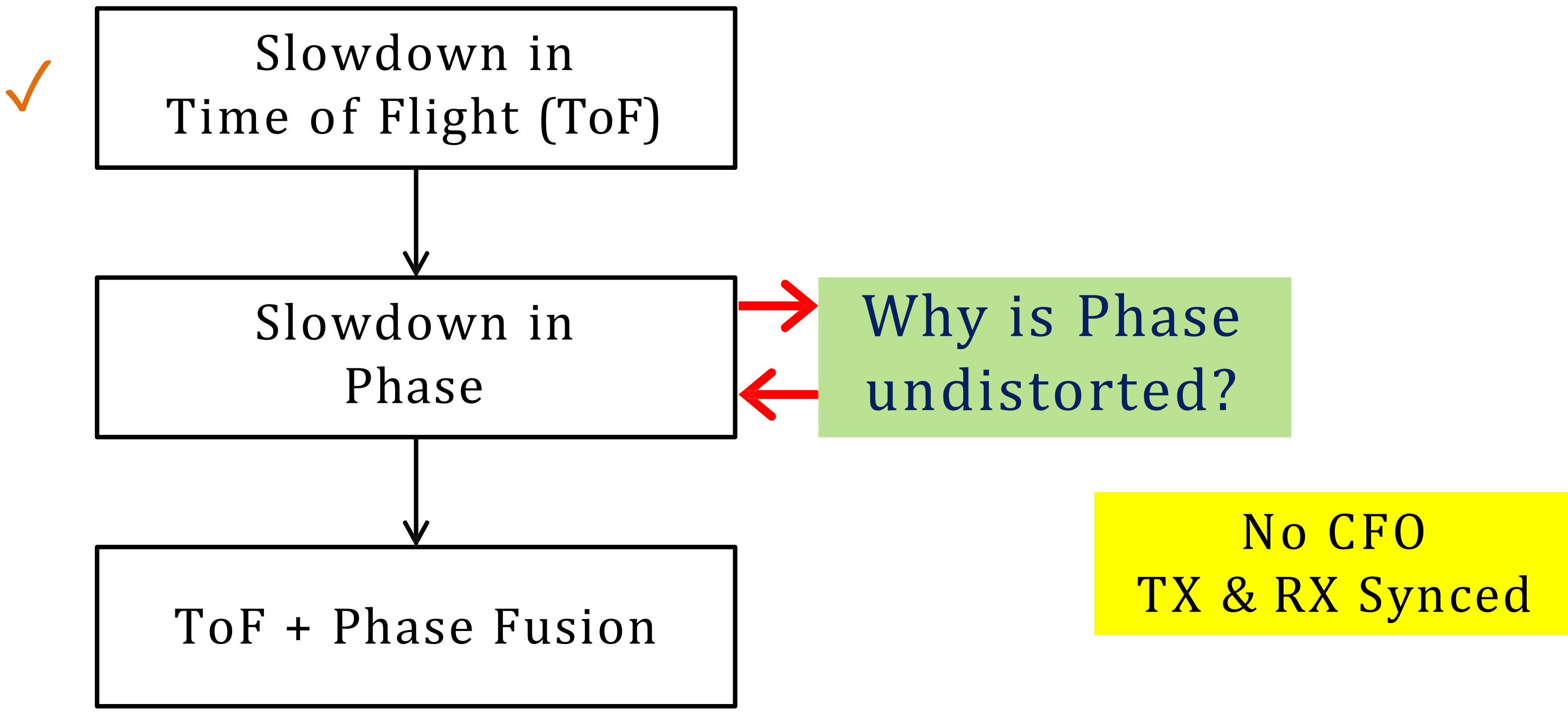


Why?

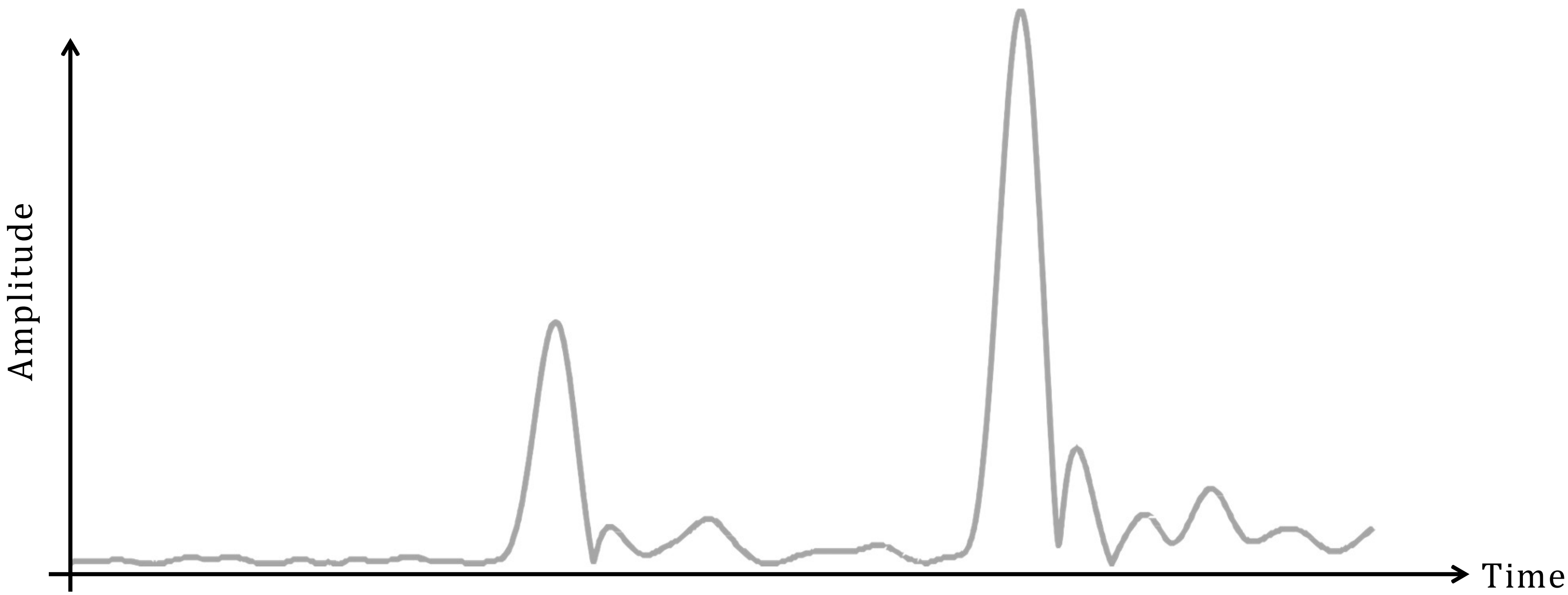


Slowdown in Time of Flight (ToF)
Slowdown in Phase
Why is Phase undistorted?
ToF + Phase Fusion

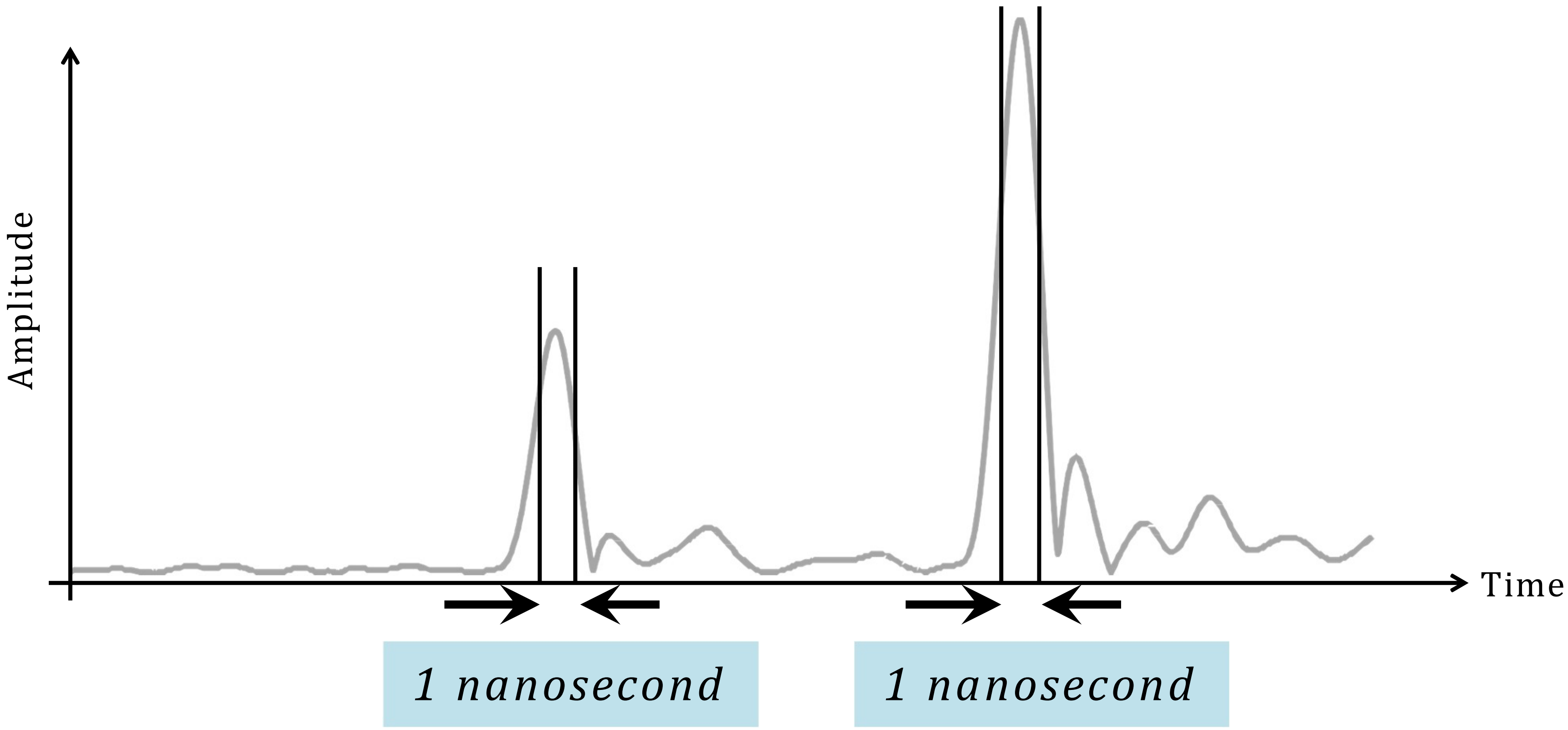
Why?


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

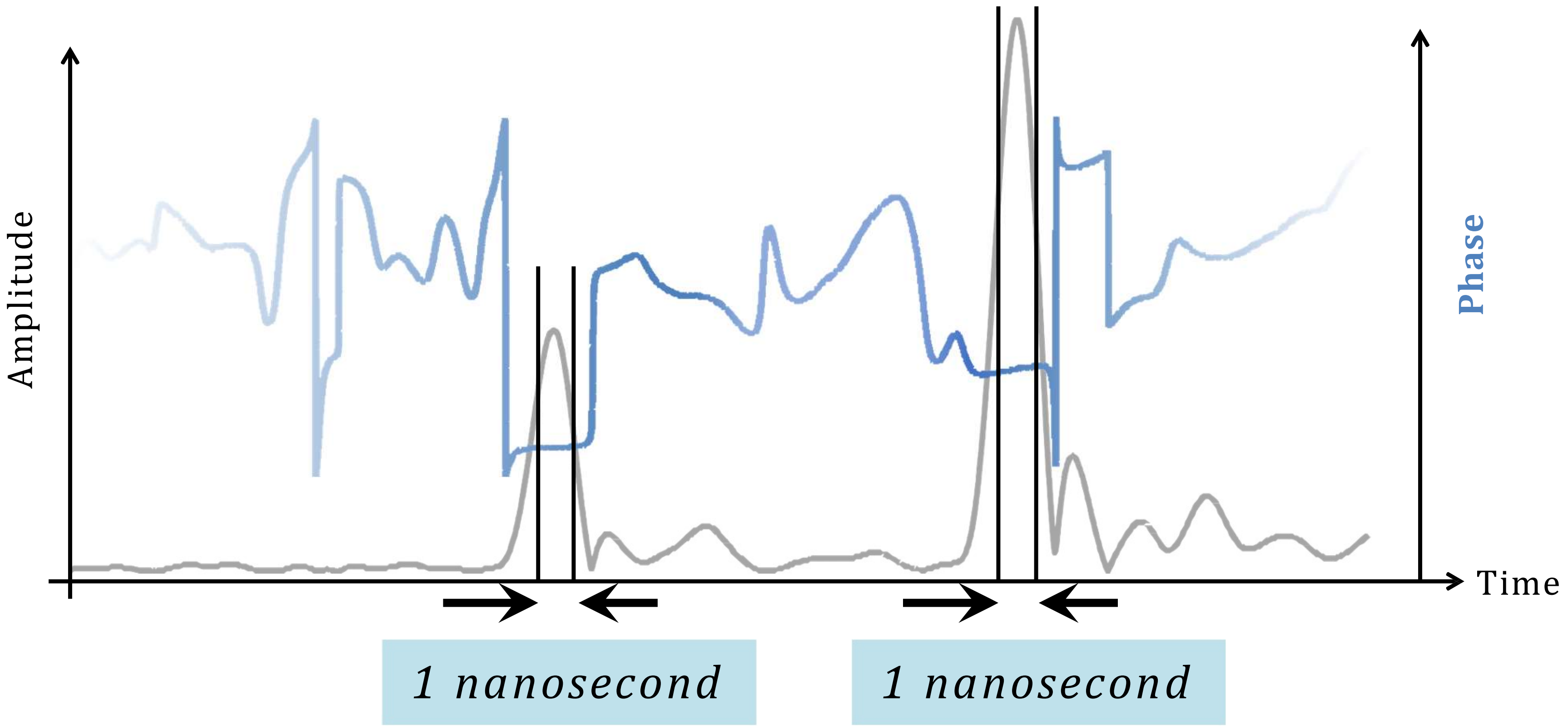
Phase to the Rescue



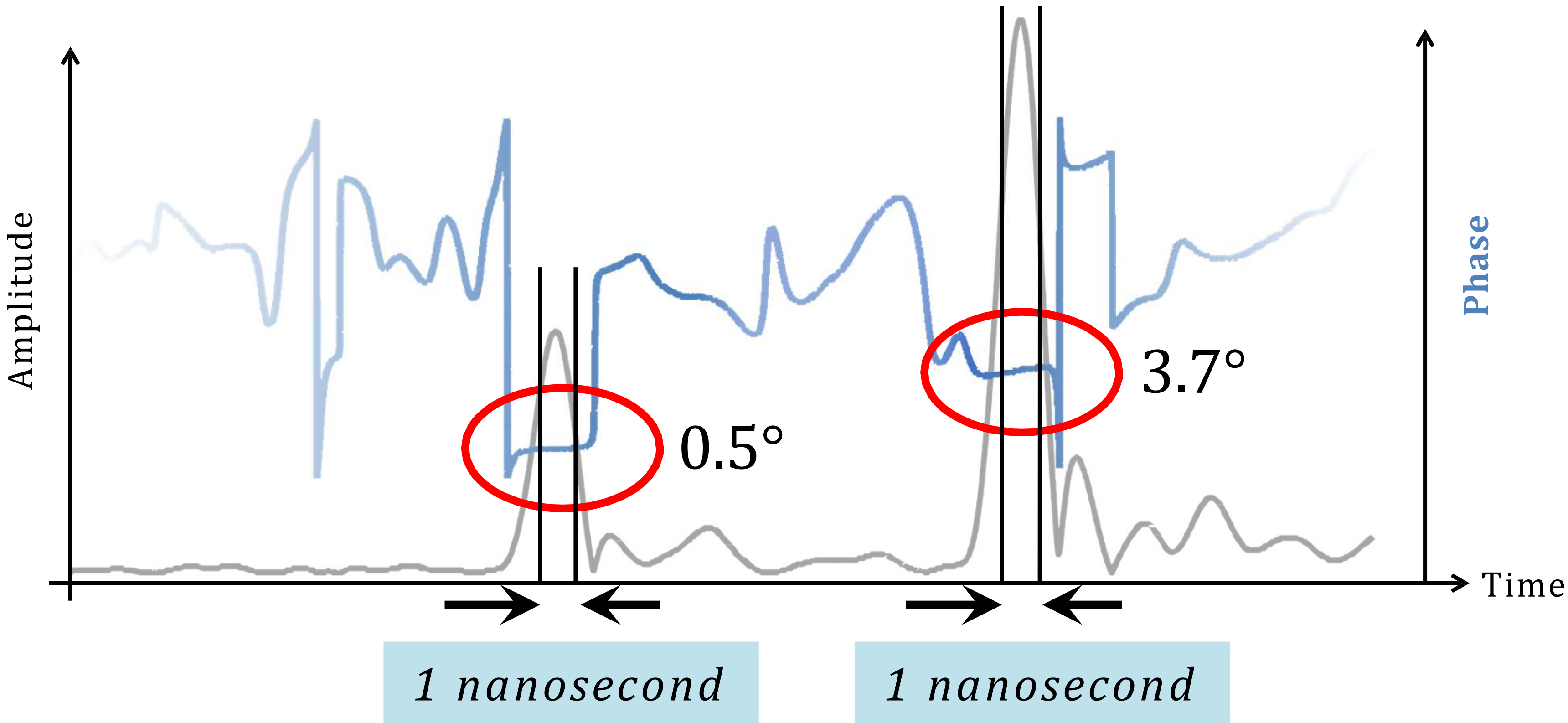
Phase to the Rescue



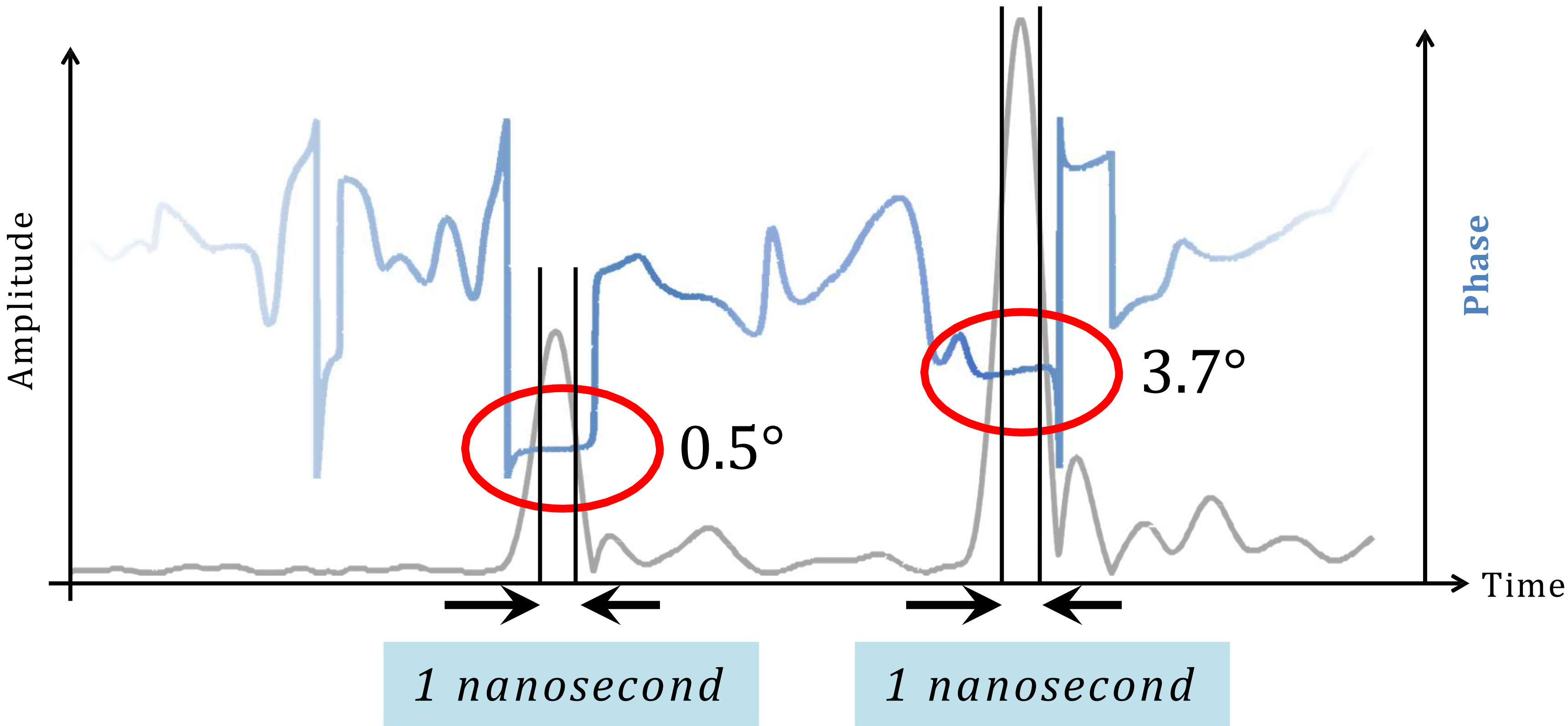
Phase to the Rescue



Phase to the Rescue

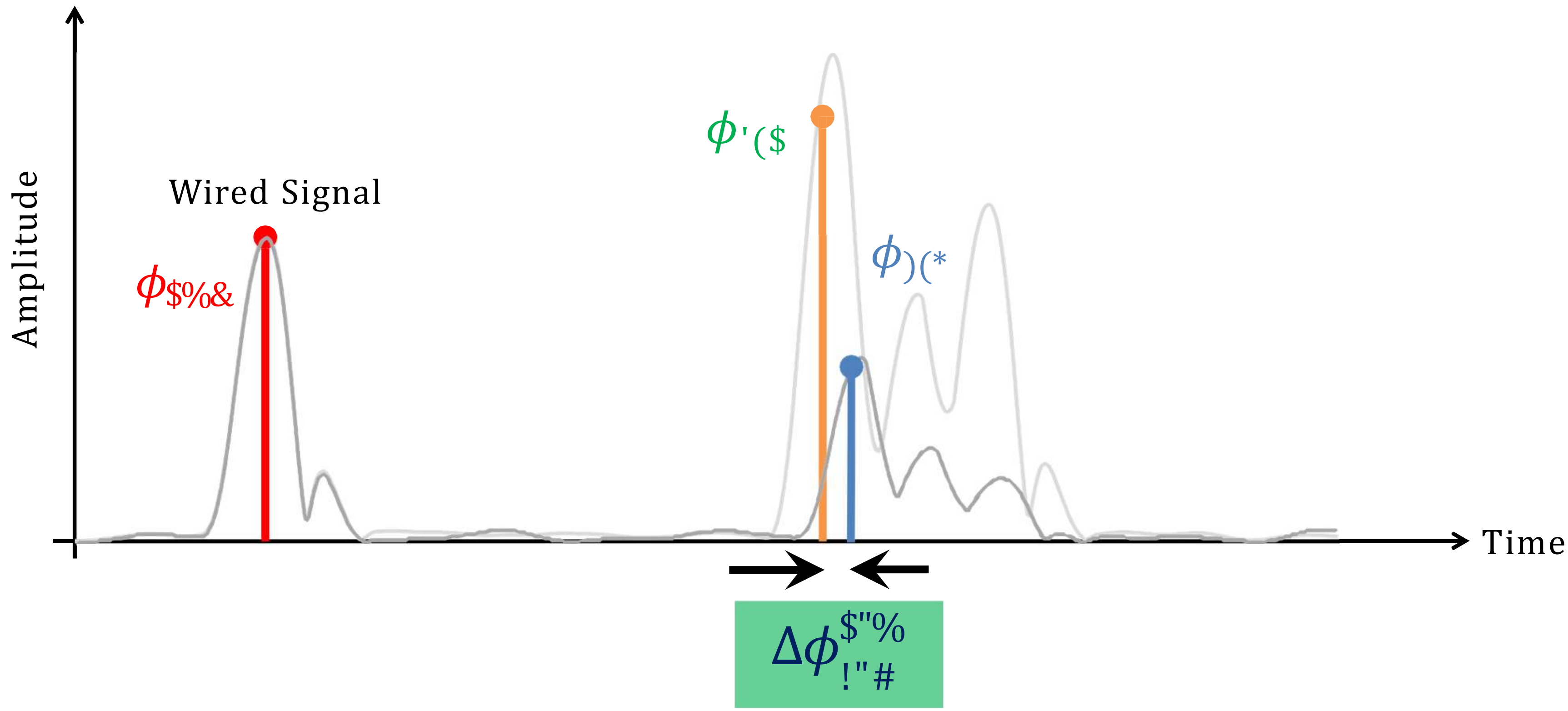


Phase to the Rescue



Phase is undistorted and stable

Double Differencing – Phase



$$\Delta\phi^{!"\#}_{'"\%} = \left(\phi_{!"\#} - \phi_{\%\&(}\right) - \left(\phi_{'"\%} - \phi_{\%\&(}\right)$$

Fuse time + phase ➔ Refractive index

$\Delta T^{!"\#}_{'"\%}$ **in nanoseconds**

$\Delta\phi^{\%"\&}_{'"\#}$ **in picoseconds**

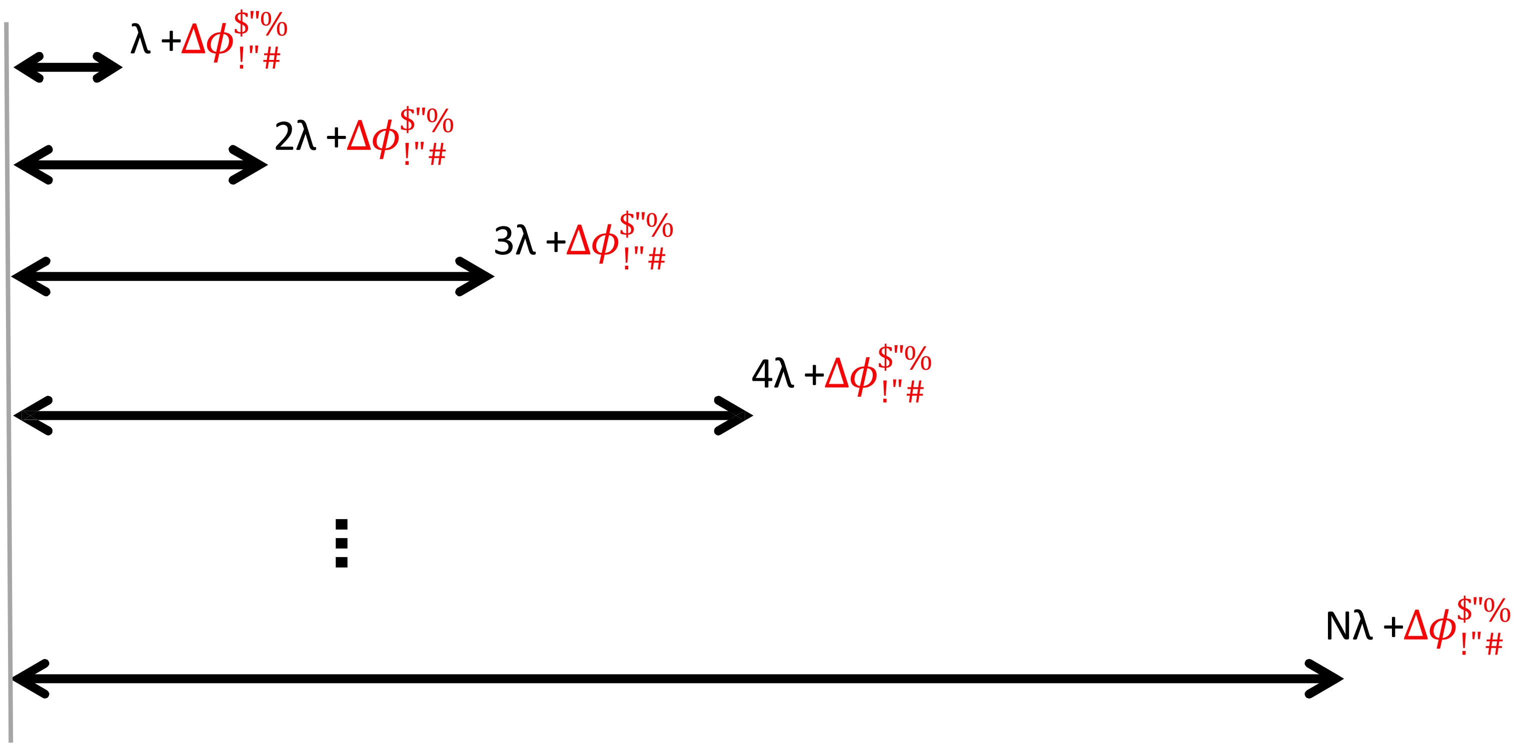
Phase Wraps:

Additional Distance $\Delta d^{!"\#}_{'"\%}$ = N λ + $\Delta \phi^{!"\#}_{'"\%}$

Phase Wraps:

Additional Distance $\Delta d^{!"\#}_{'"\%} = N\lambda + \Delta\phi^{!"\#}_{'"\%}$

For a given $\Delta\phi^{\$"\%}_{!"\#}$, possible $\Delta d^{\$"\%}_{!"\#}$ distances can be:



Phase Wraps: Additional Distance $\Delta d^{!"\#}_{'"\%}$ = N λ + $\Delta\phi^{!"\#}_{'"\%}$

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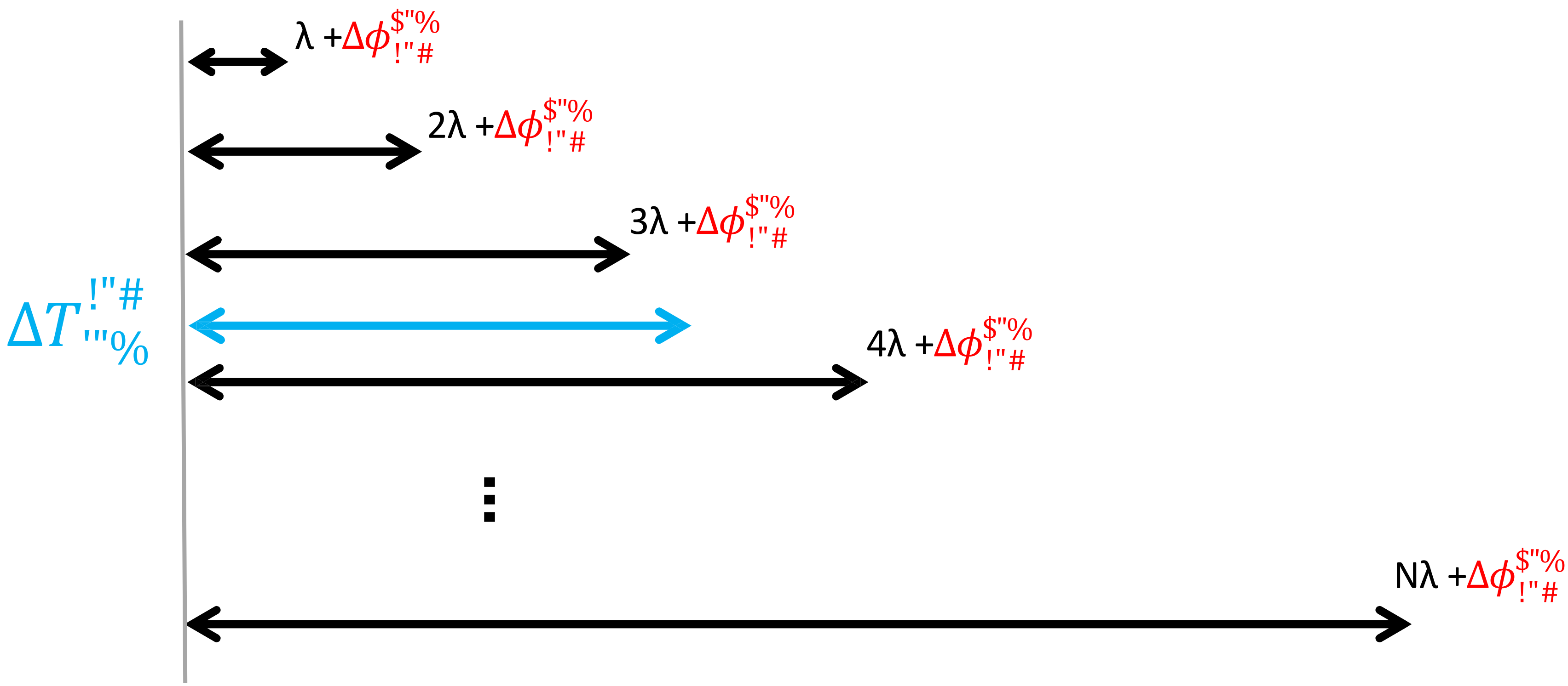

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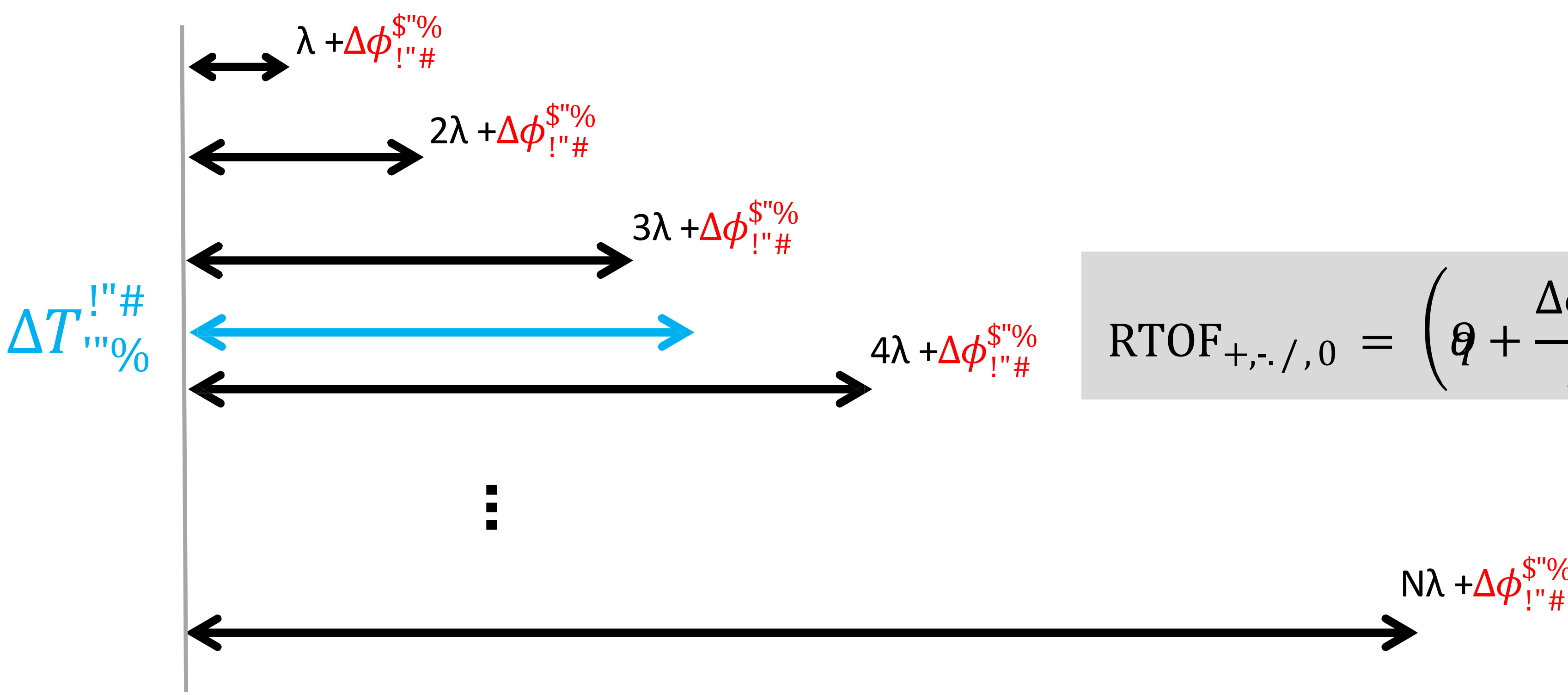


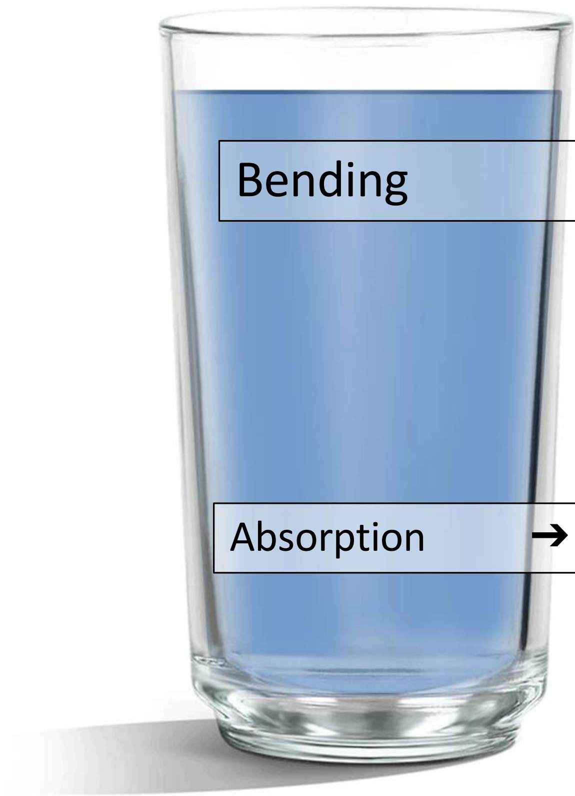
$$\mathrm{RTOF}_{+,-./,0} = \left(q + \frac{\Delta\phi'^{)(*}_{(\$}}{2\pi}\right)\frac{\lambda_1}{c}$$

Finally, we have …

$$\mathrm{RTOF}_{+,-./,0} = \left(q + \frac{\Delta\phi^{)(*}_{'(\$}}{2\pi}\right)\frac{\lambda_1}{c} = ToF_{()*} - ToF_{+),} = \frac{d}{v} - \frac{d}{c}$$

$$Refractive\ Index = \frac{c}{v} = \frac{\left(q + \frac{\Delta\phi^{!"\#}_{'''\%}}{2\pi}\right)\lambda_{)}}{d} + 1$$

Key Properties of Liquid

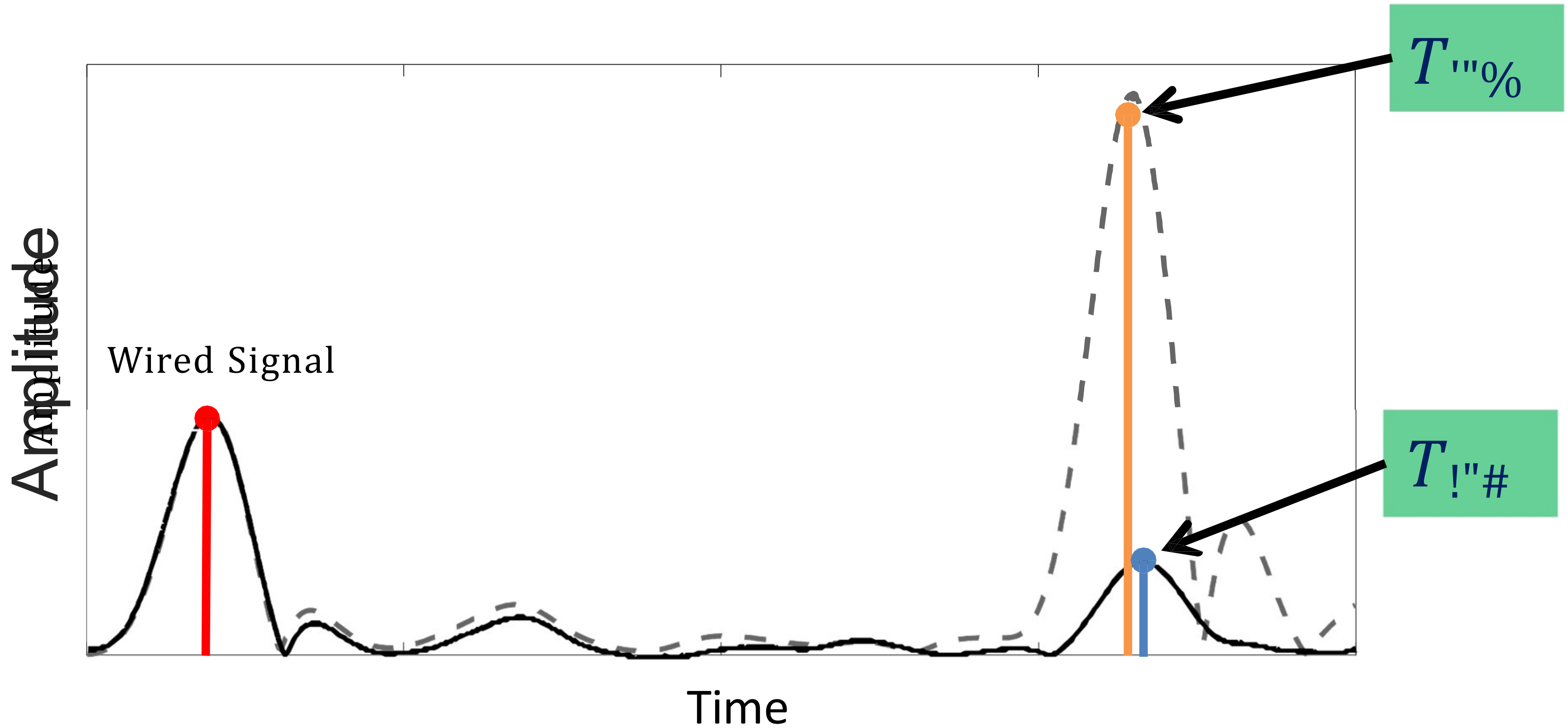


Bending ➔ Refractive Index ✓

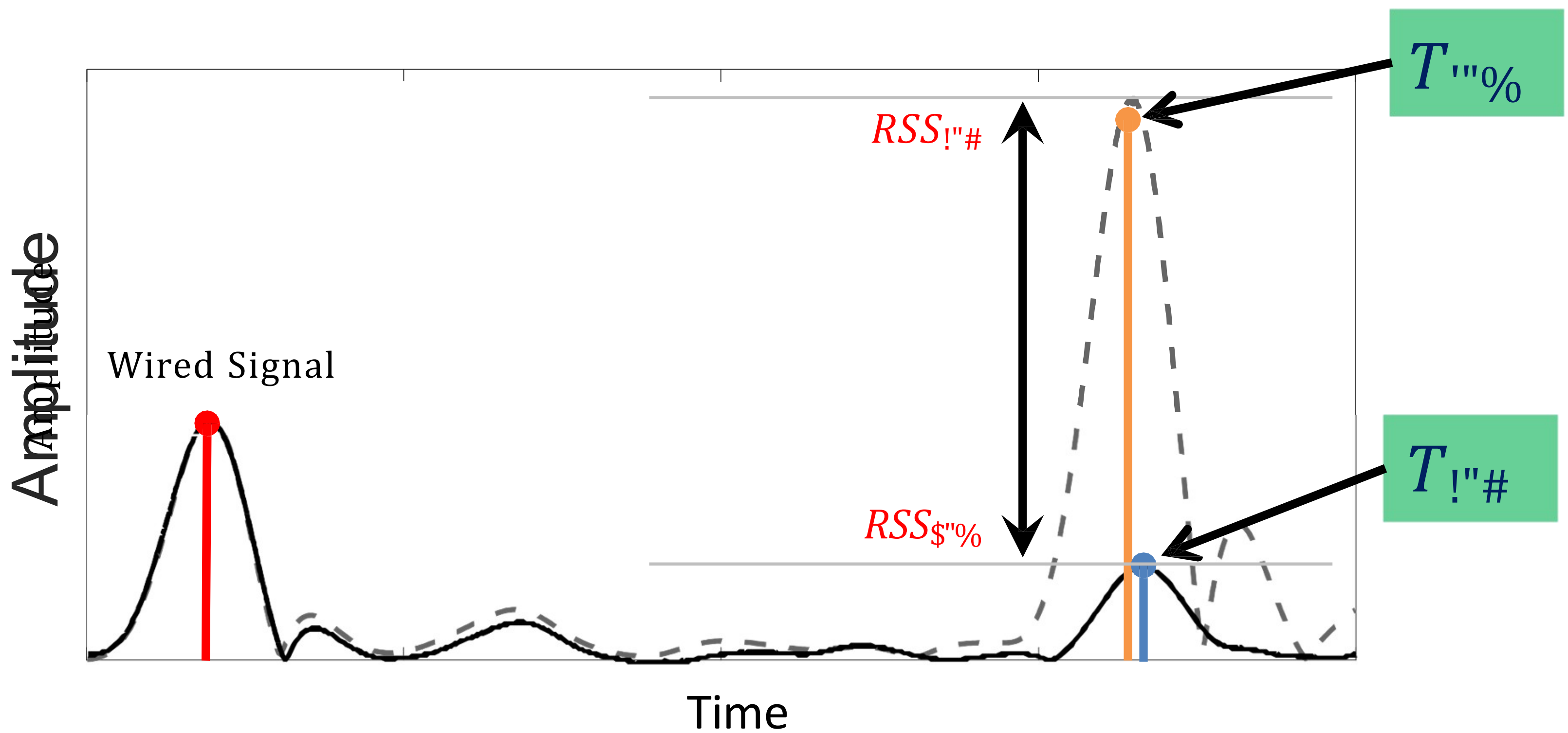
Absorption ➔ Attenuation Factor

} Unique Tuple

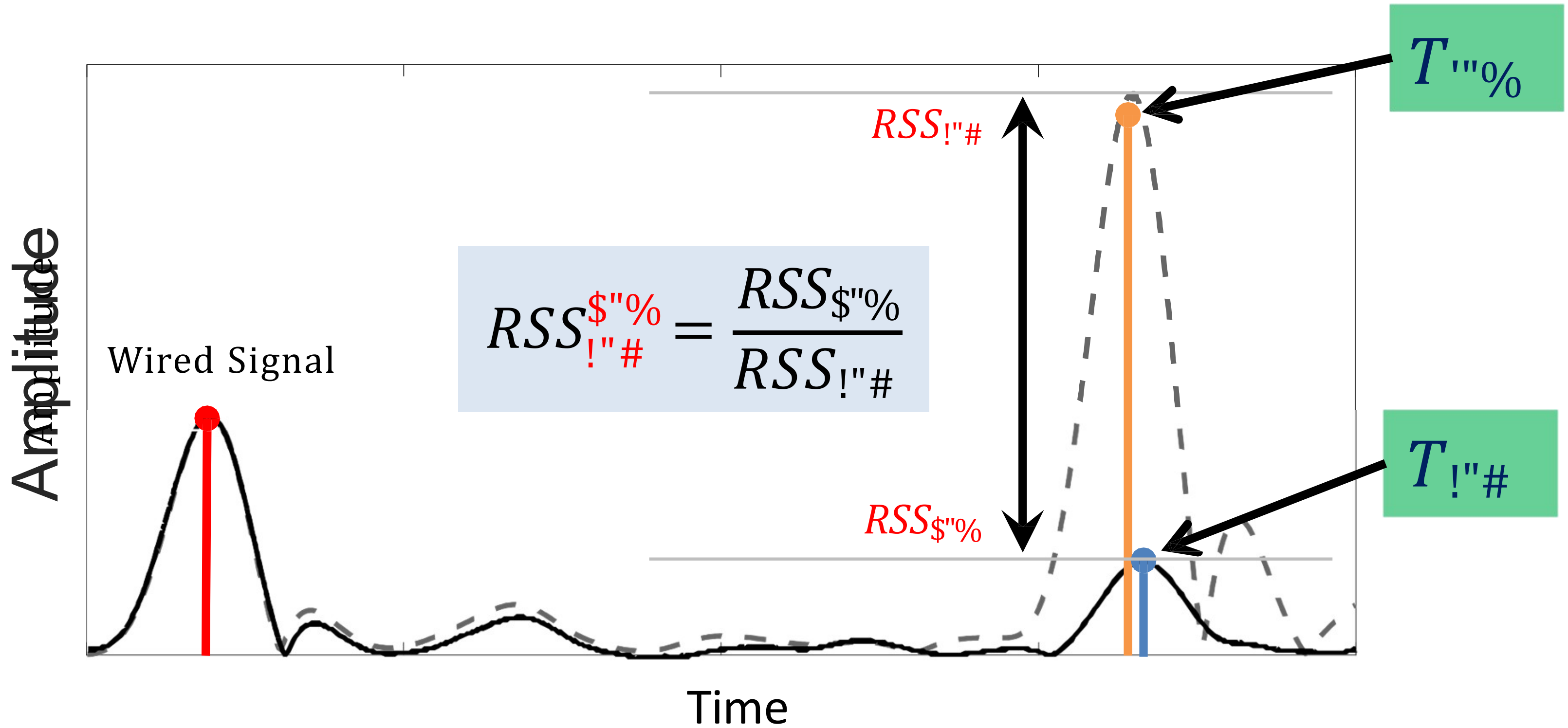
Estimating Attenuation



Estimating Attenuation



Estimating Attenuation



Obtaining Complex Permittivity

$$Complex\ Permittivity = \epsilon^{*} + j\epsilon''$$

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

Obtaining Complex Permittivity

$$Complex\ Permittivity = \epsilon^{*} + j\epsilon''$$

$$Refractive\ Index = \sqrt{\frac{1}{2}\epsilon^{2}\left\{\sqrt{1+\left(\frac{\epsilon^{22}}{\epsilon^{2}}\right)^{3}}+1\right\}}$$

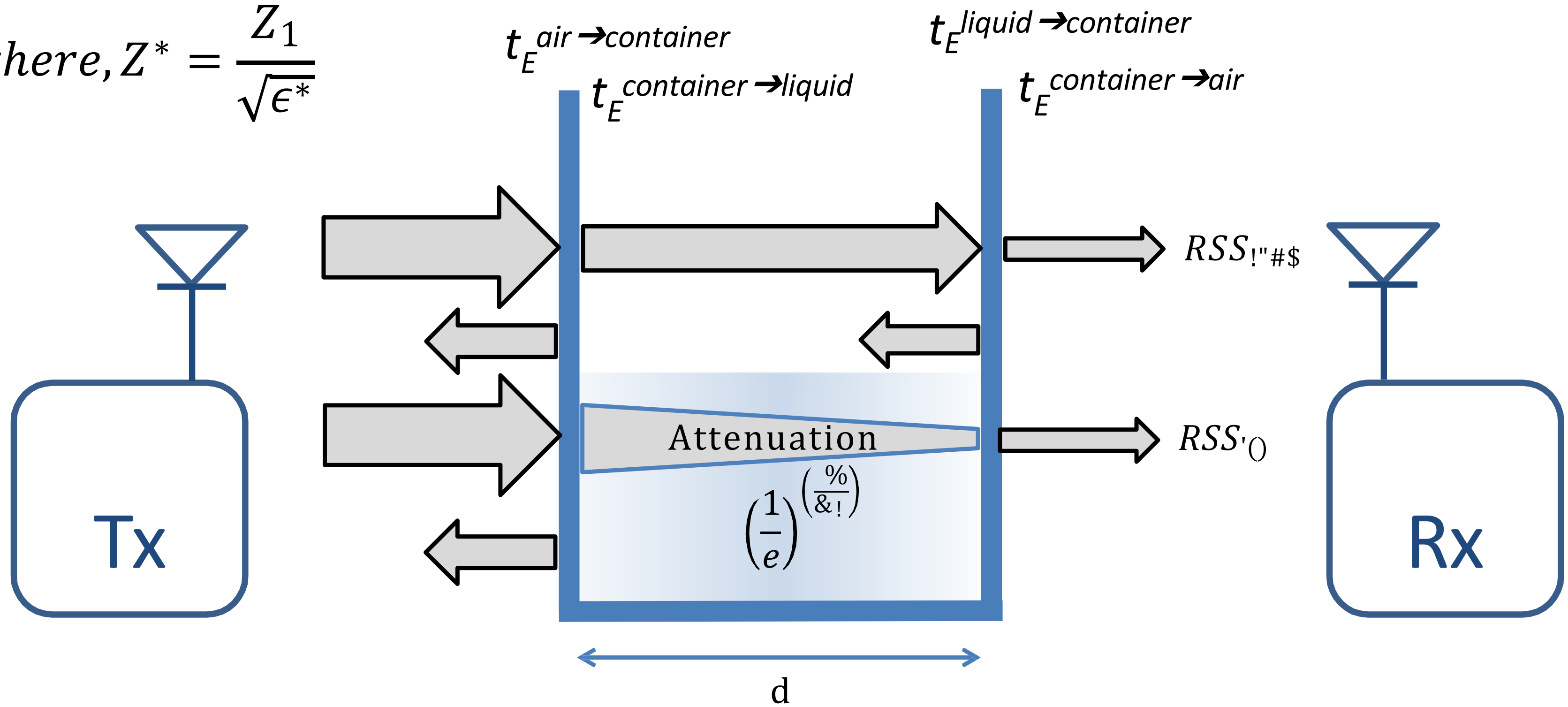
$$Attenuation\ Factor = \frac{\lambda_1}{2\pi}\sqrt{\frac{2}{\epsilon'\left(\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^{3}}-1\right)}}$$

Solve for ϵ^{*} and ϵ^{**}

Container Compensation

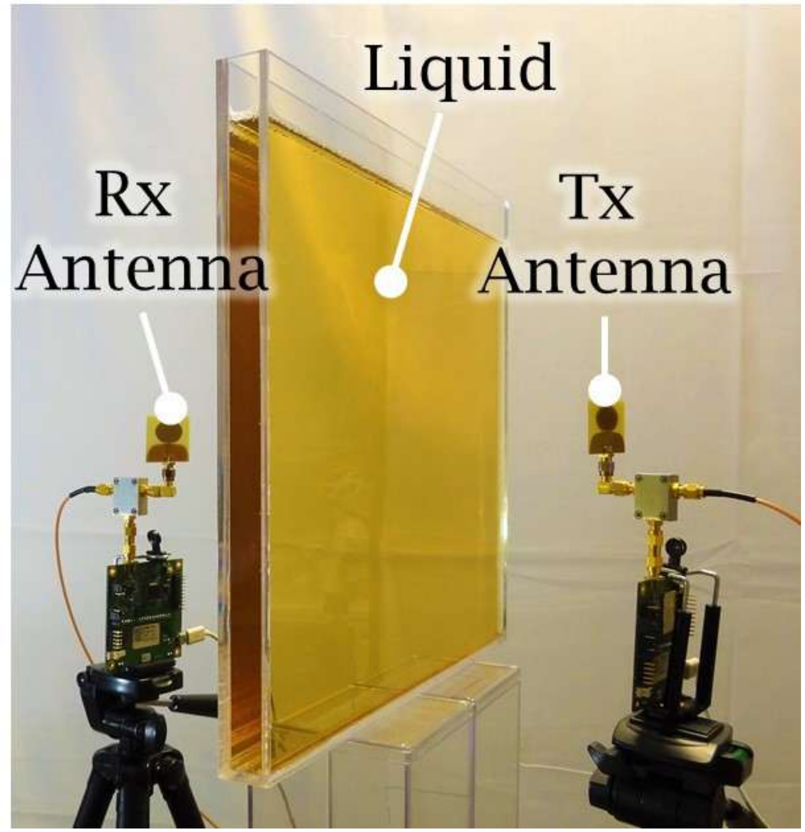
$$t_4 = \frac{2Z_3}{Z_3 + Z_5}$$

$$where, Z^* = \frac{Z_1}{\sqrt{\epsilon^*}}$$

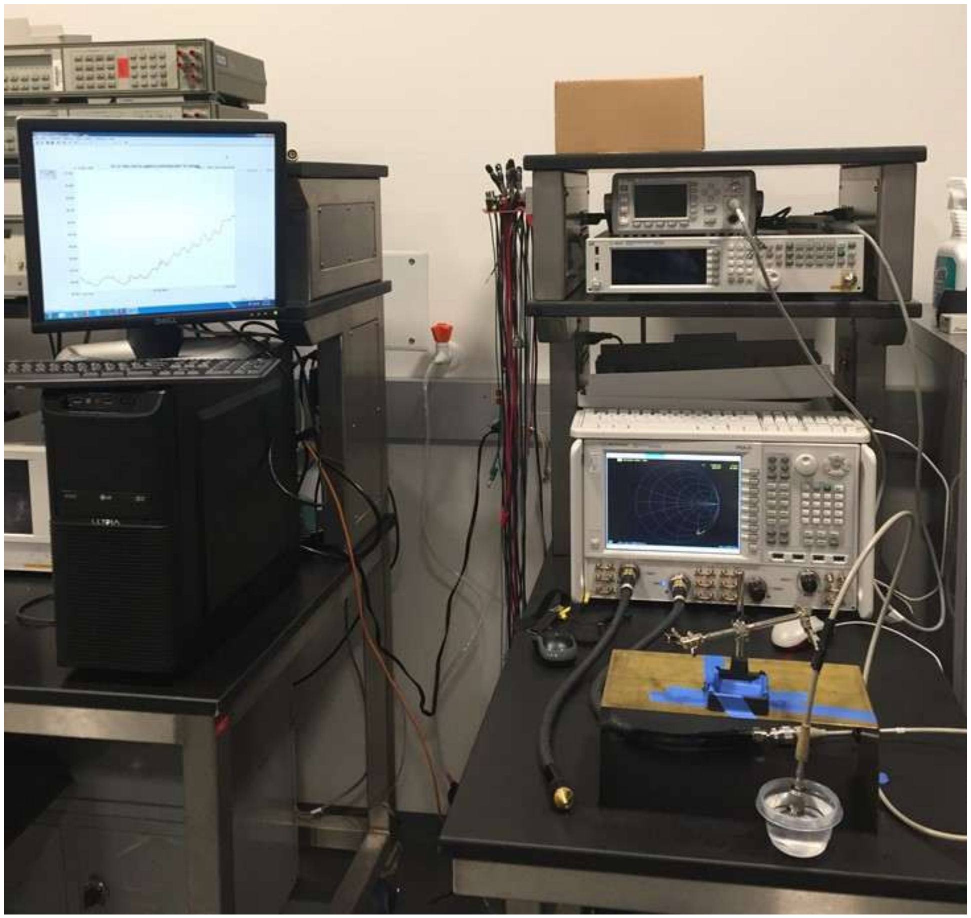


Experimental Setup

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

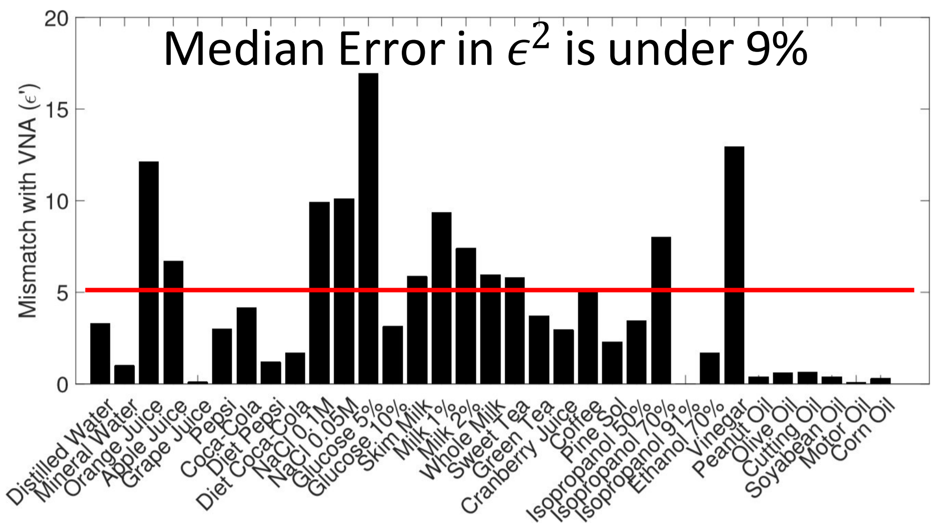


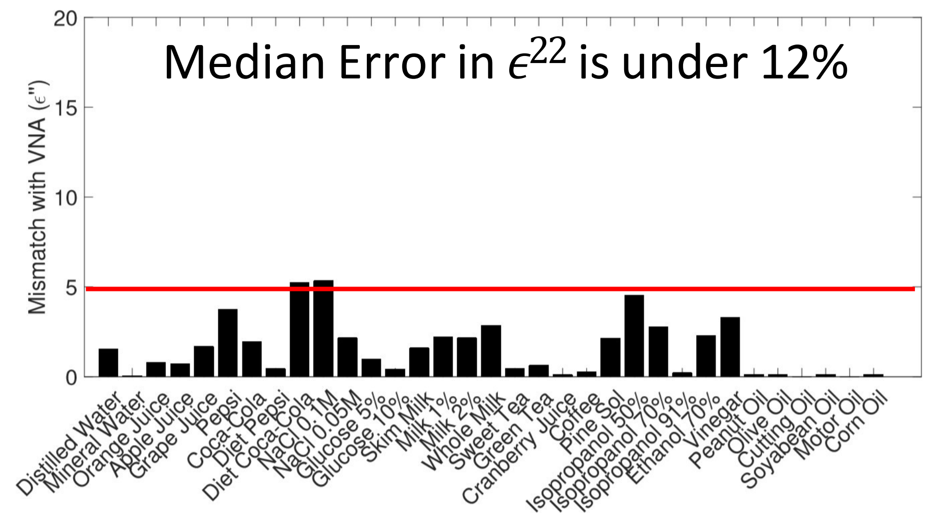
Baseline: Vector Network Analyzer



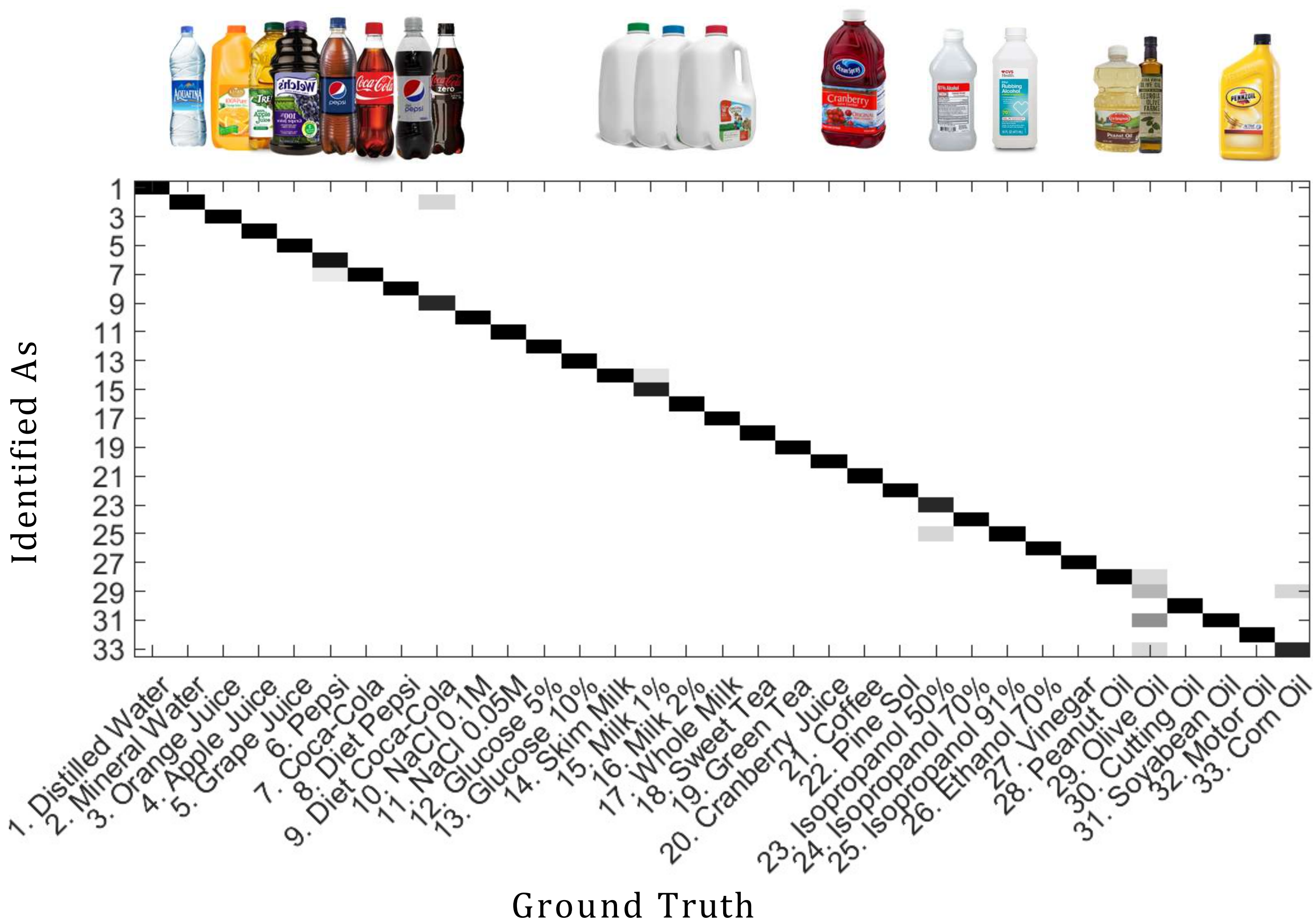
- VNA + Dielectric Probe method for creating a baseline
- Measures the liquid's complex permittivity
- Published error is 5%

Results – Permittivity

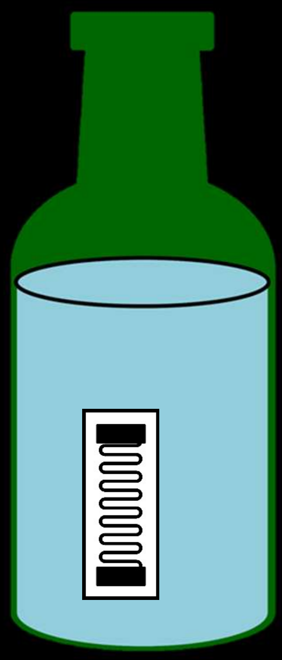




Results – Liquid Identification



Approach: Exploit the wireless interaction between an RFID and the content



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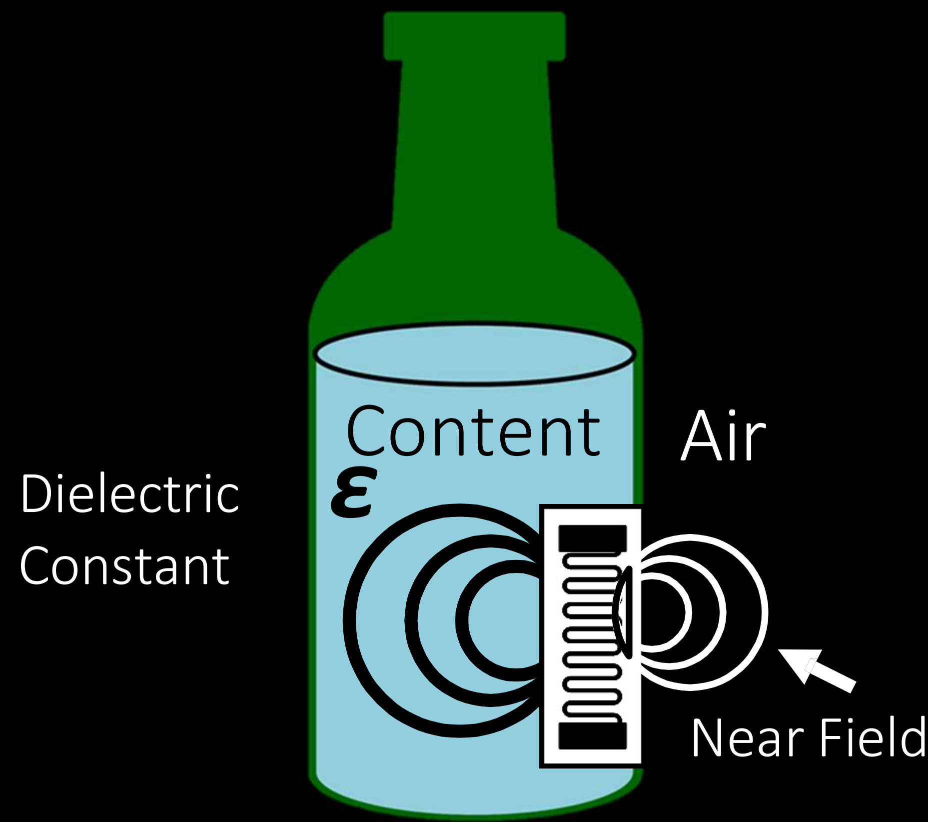

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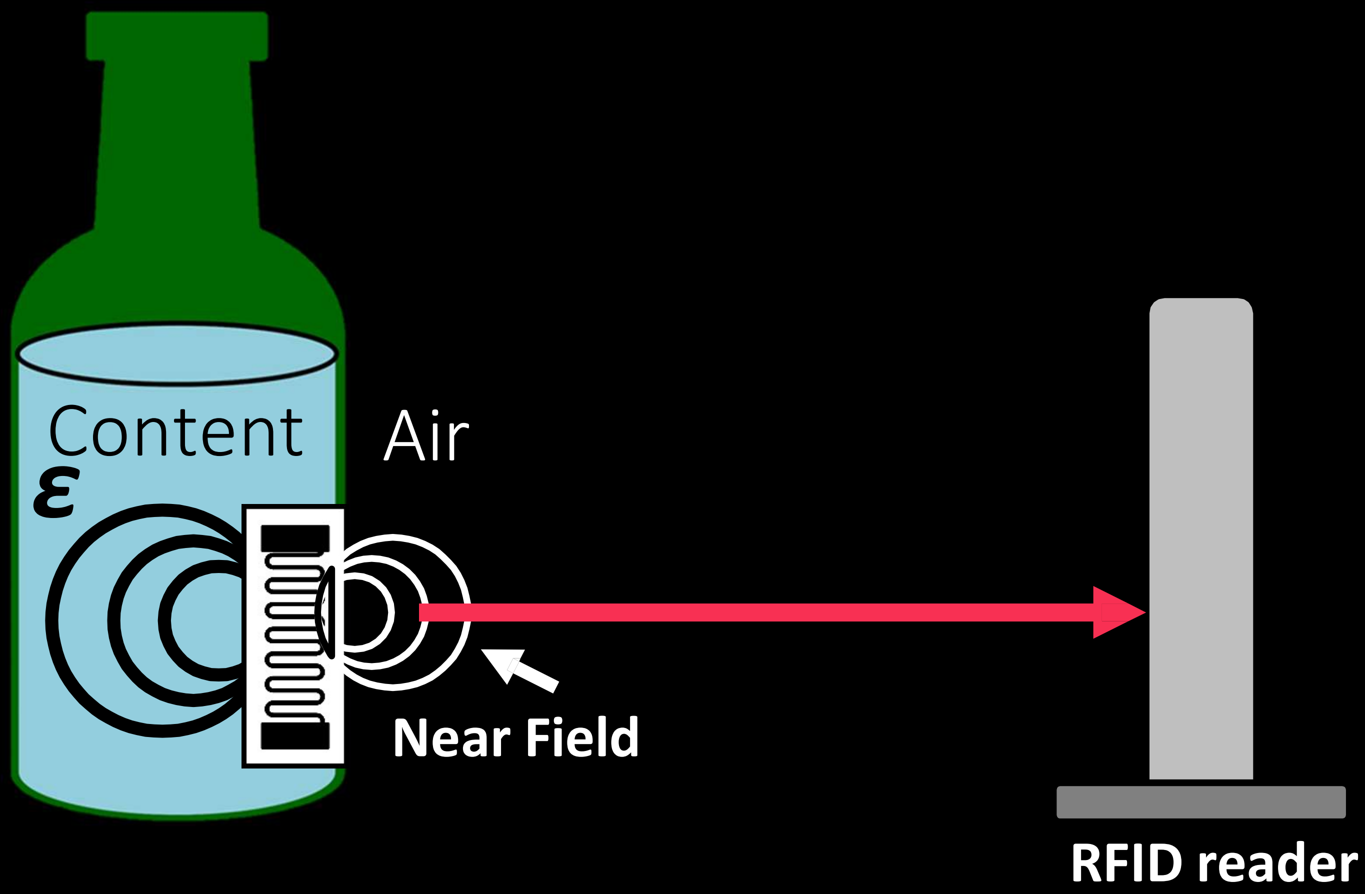

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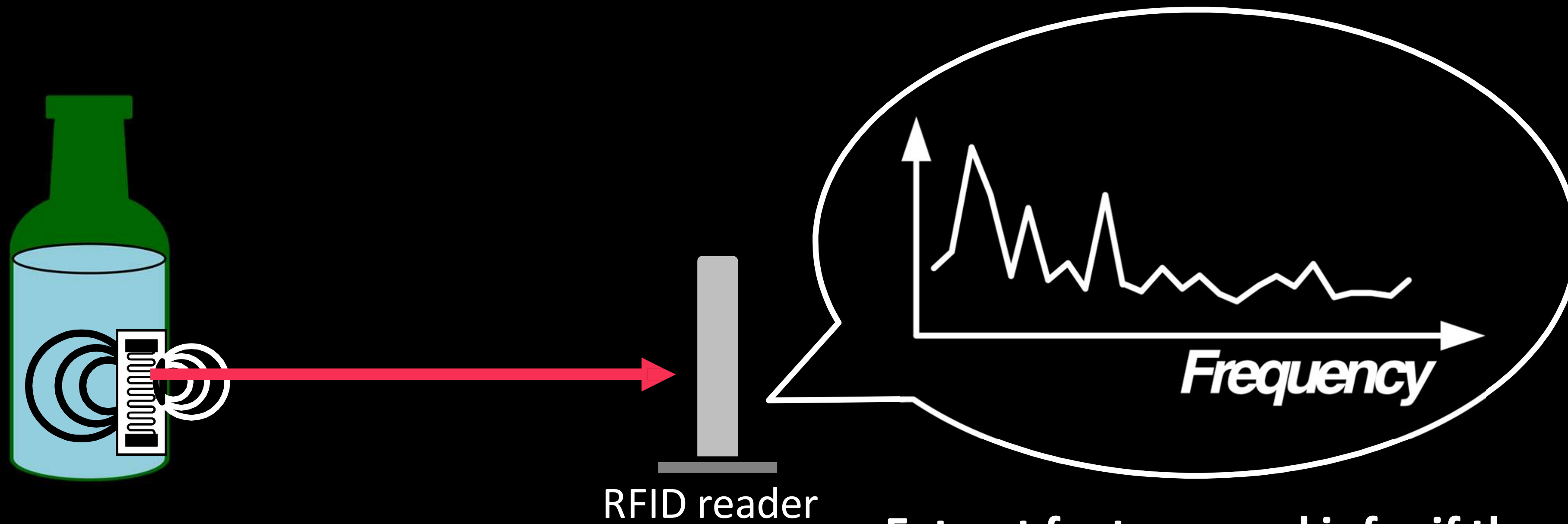
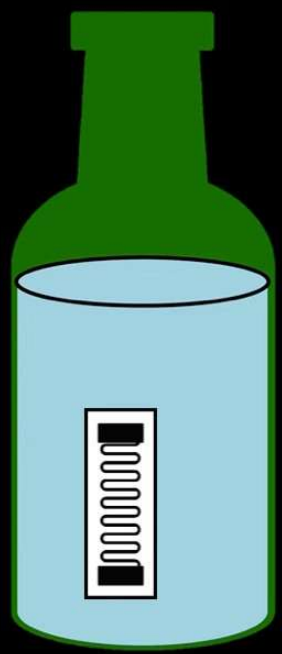


Extract features and infer if the content is fake/authentic

We developed a system that uses the RFID stickers already on hundreds of billions of items

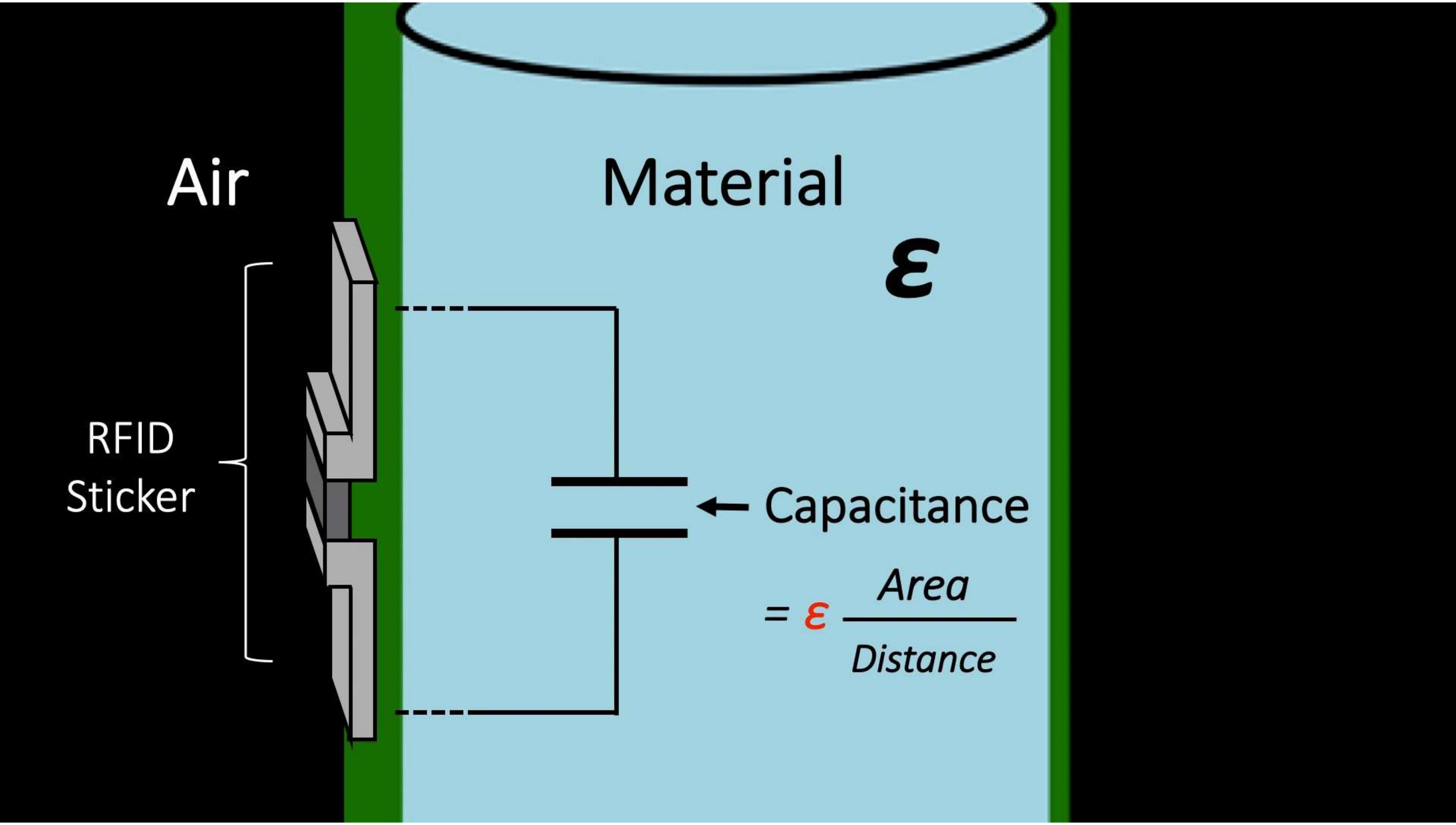


We developed a system that uses the RFID stickers already on hundreds of billions of items

to sense properties of food in closed containers

We developed a system that uses the RFID stickers already on hundreds of billions of items

RFID wirelessly interacts with material inside the bottle


Air
Material
ε
RFID
Sticker
Capacitance
= ε Area / Distance

Challenge: Dielectric sensing requires measuring the response over a large bandwidth (many frequencies)

RFIDs are designed to be narrowband to optimize energy-harvesting

↓

Use 2 frequency excitation (RFind) to sense a bandwidth 10,000x larger than their communication bandwidth

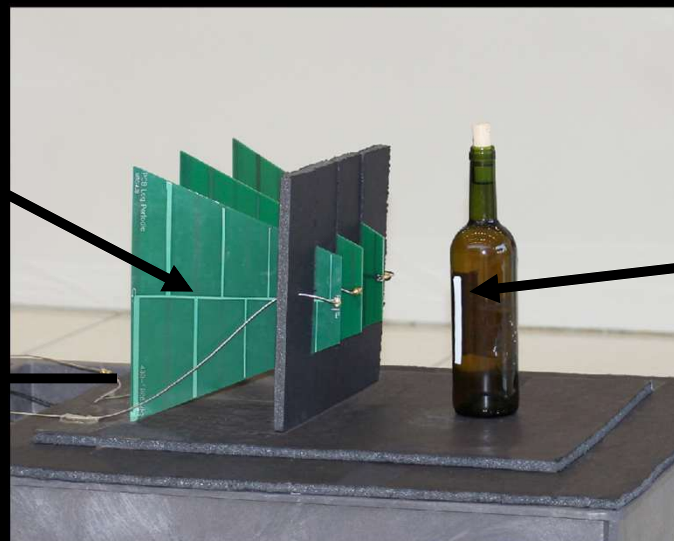
without *any* hardware modification to the RFIDs

Implementation

LP0410 Antenna

USRP N210

USRP X310



Off-the-shelf RFIDs
(Alien, Smartrac)

- Run the EPC-Gen2 Protocol
- Two-frequency Excitation (MobiCom'17)
  - 500-1000 MHz
  - Features: amplitude, phase

- 20 Different environments including kitchen, supermarket style, dining tables, etc
- 2,048 samples in total

Applications Tested

Tainted /Diluted Alcohol

Adulterated Baby Formula

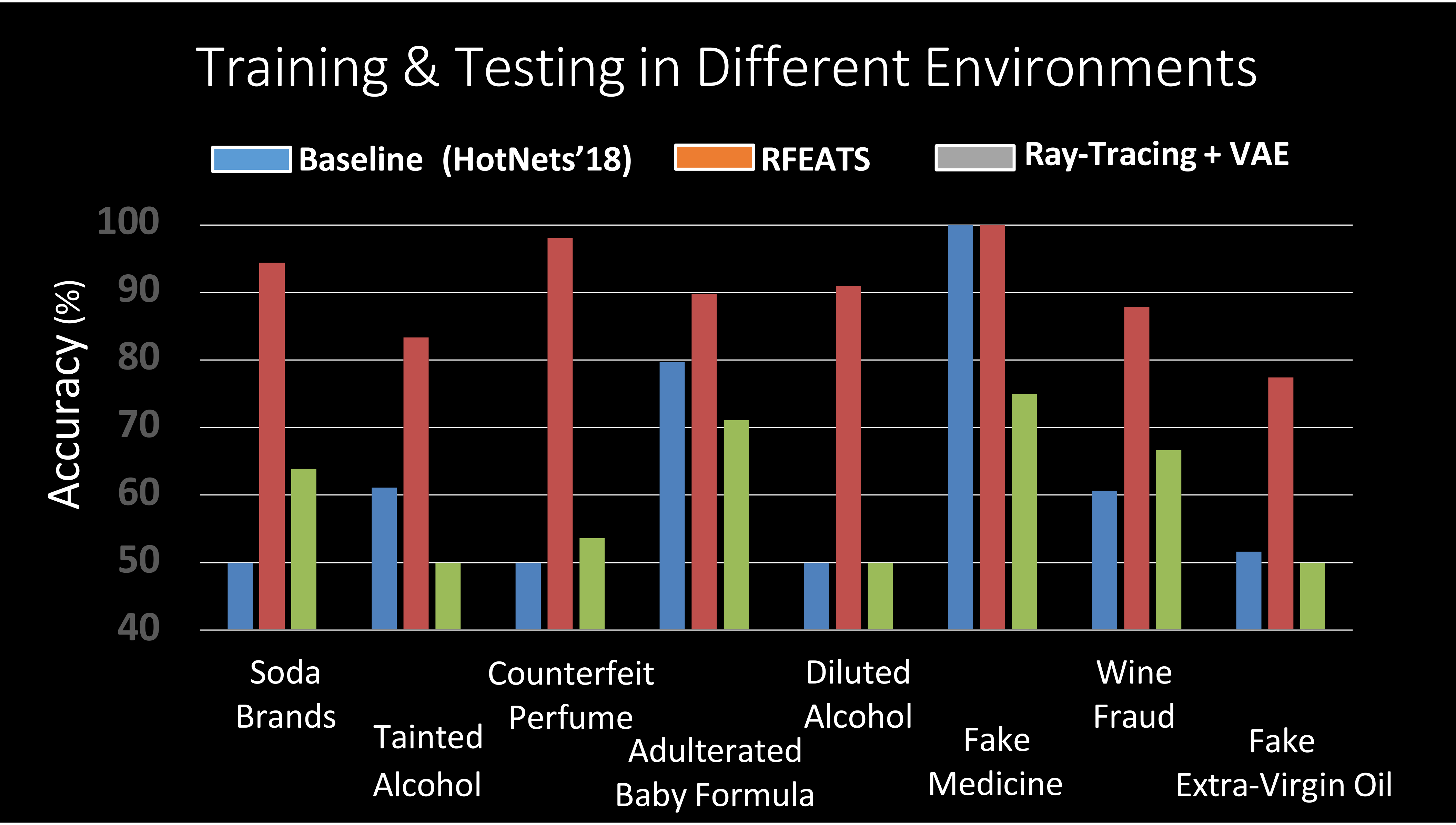
Fake Medicine

Counterfeit Perfume

Fake Extra-Virgin Oil

Soda Brand

Wine Fraud


Training & Testing in Different Environments
Baseline (HotNets'18)
RFEATS
Ray-Tracing + VAE
Accuracy (%)
100
90
80
70
60
50
40
Soda Brands
Tainted Alcohol
Counterfeit Perfume
Adulterated Baby Formula
Diluted Alcohol
Fake Medicine
Wine Fraud
Fake Extra-Virgin Oil

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

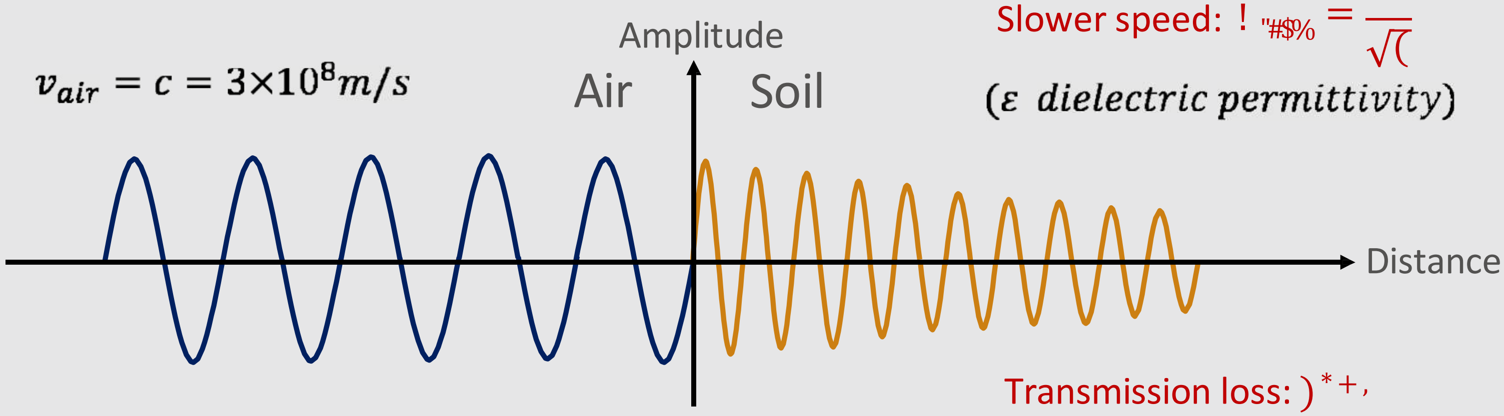
- Tensiometer

- 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



Slower speed: ! "#$% = ' / √(

(ε *dielectric permittivity*)

Transmission loss:) *+,

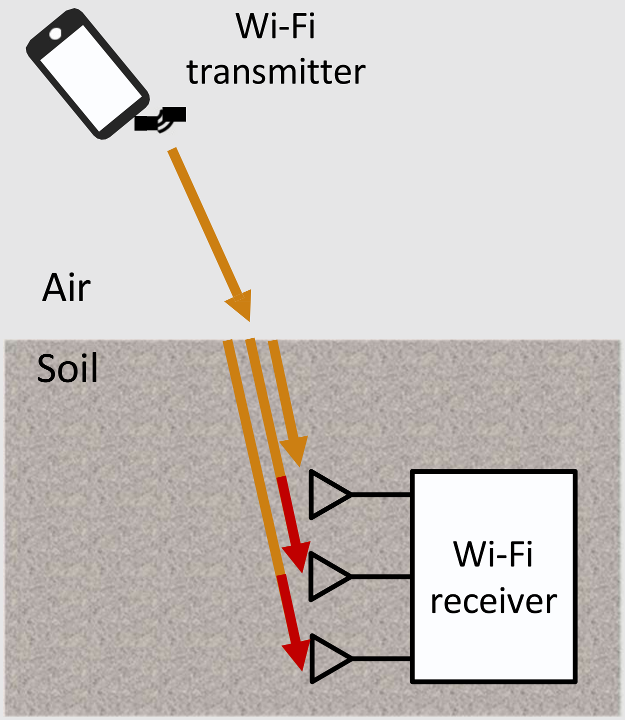
(- : /00)12/0341 '4)553'3)10, a function of EC)

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