LiqRay: Non-invasive and Fine-grained Liquid Recognition System

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Background

Fine-grained liquid recognition is a potential application in many scenarios

Allowed or not?

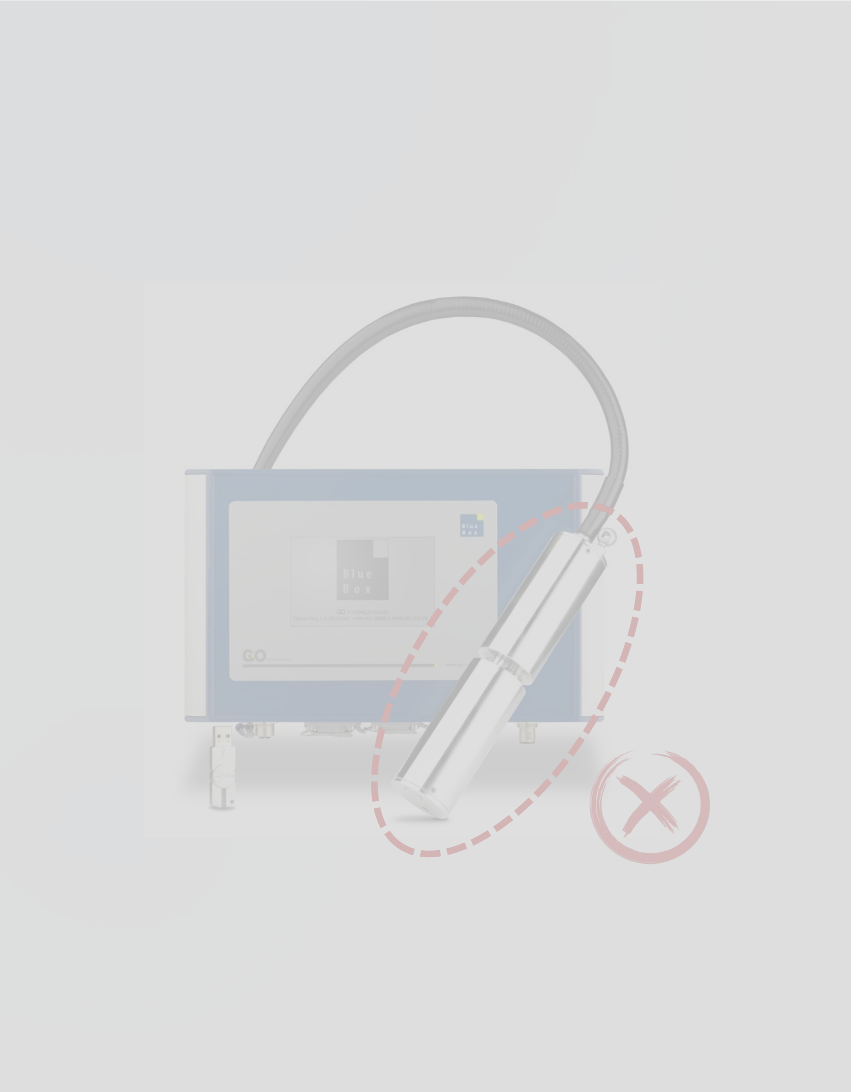
Fake or not?

Healthy or not?

Motivation

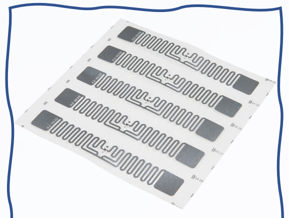
Traditional liquid identification methods need expensive equipment and will contaminate liquids

Motivation



For ease of deployment,

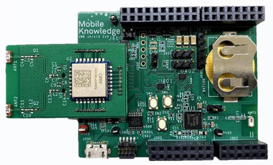
Many meaningful works based on communication devices have been proposed



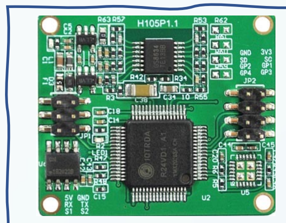
RFID

WiFi

Smartphone



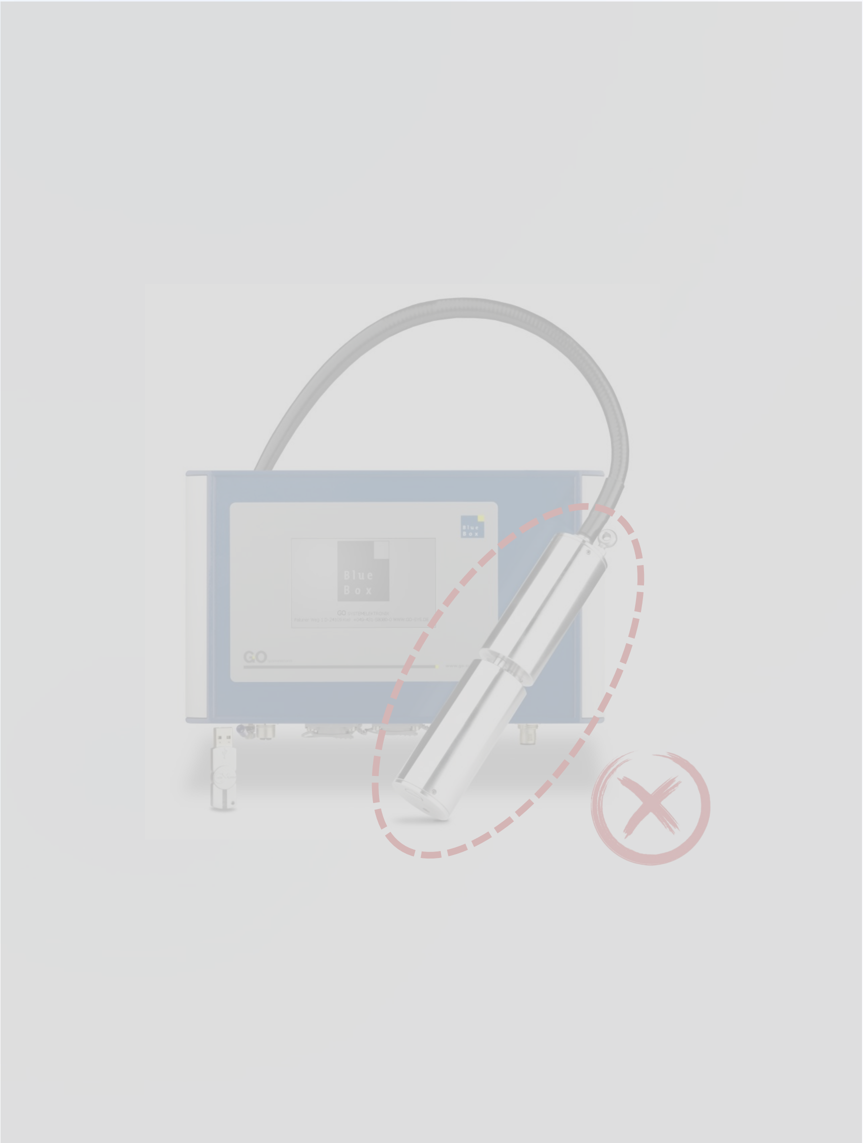
UWB



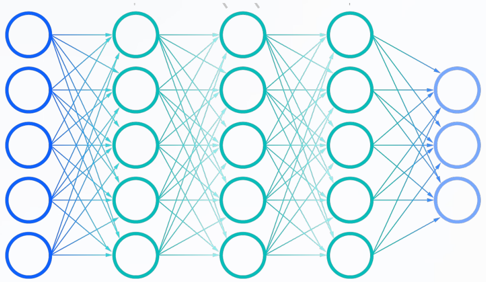
MMwave

[1] Ju. W, etc. 2017. TagScan; [2] Binbin. X,etc, 2019. Tagtag; [3] Chao. F, etc, 2019. WiMi; [4] Ashutosh. A, etc, 2018. Liquid ; [5] Yumeng. L, etc, 2021. FG-LiquID; [6] Yongzhi. H, etc, 2021, Vi-liquid;

Motivation



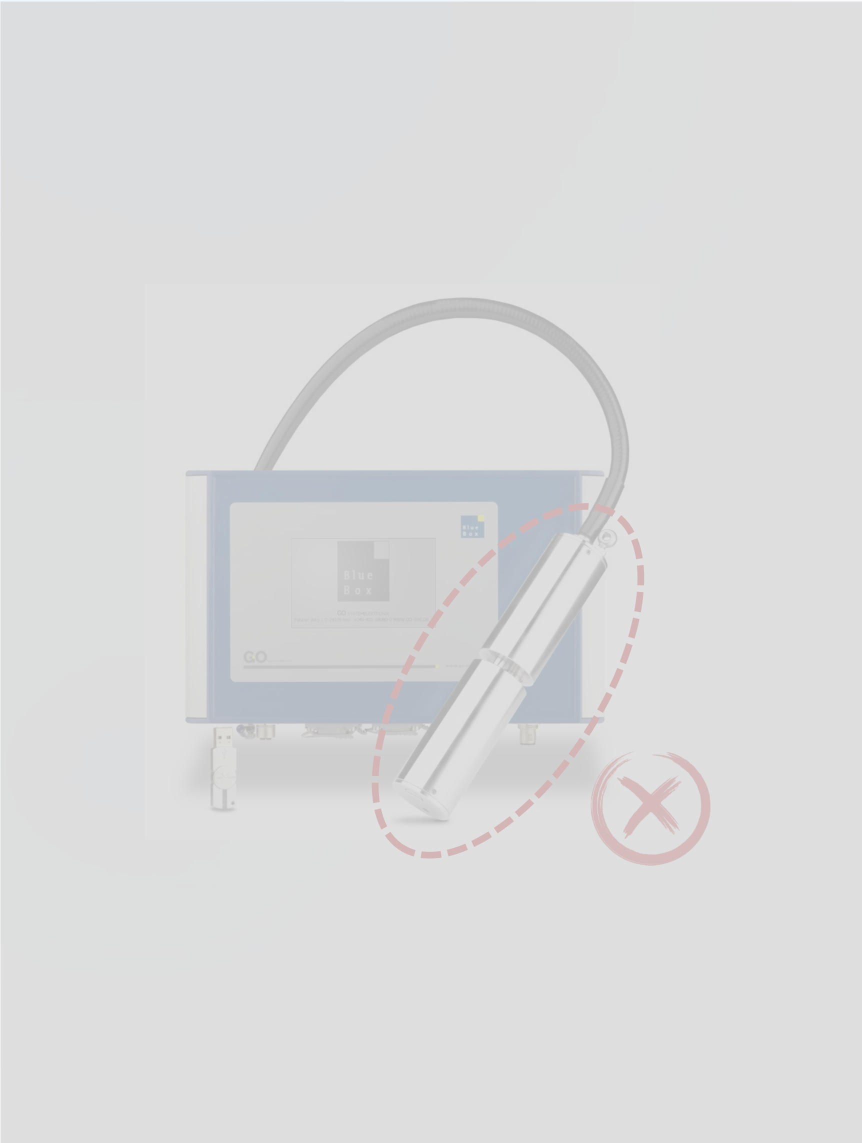
However, specific containers are usually required



Data driven

Physical model

Motivation



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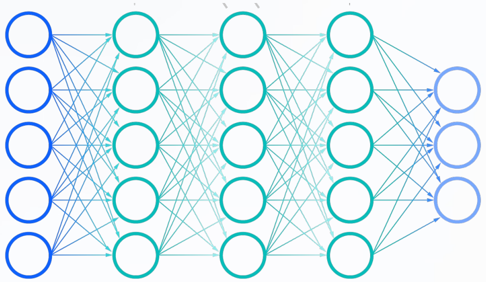


Data driven

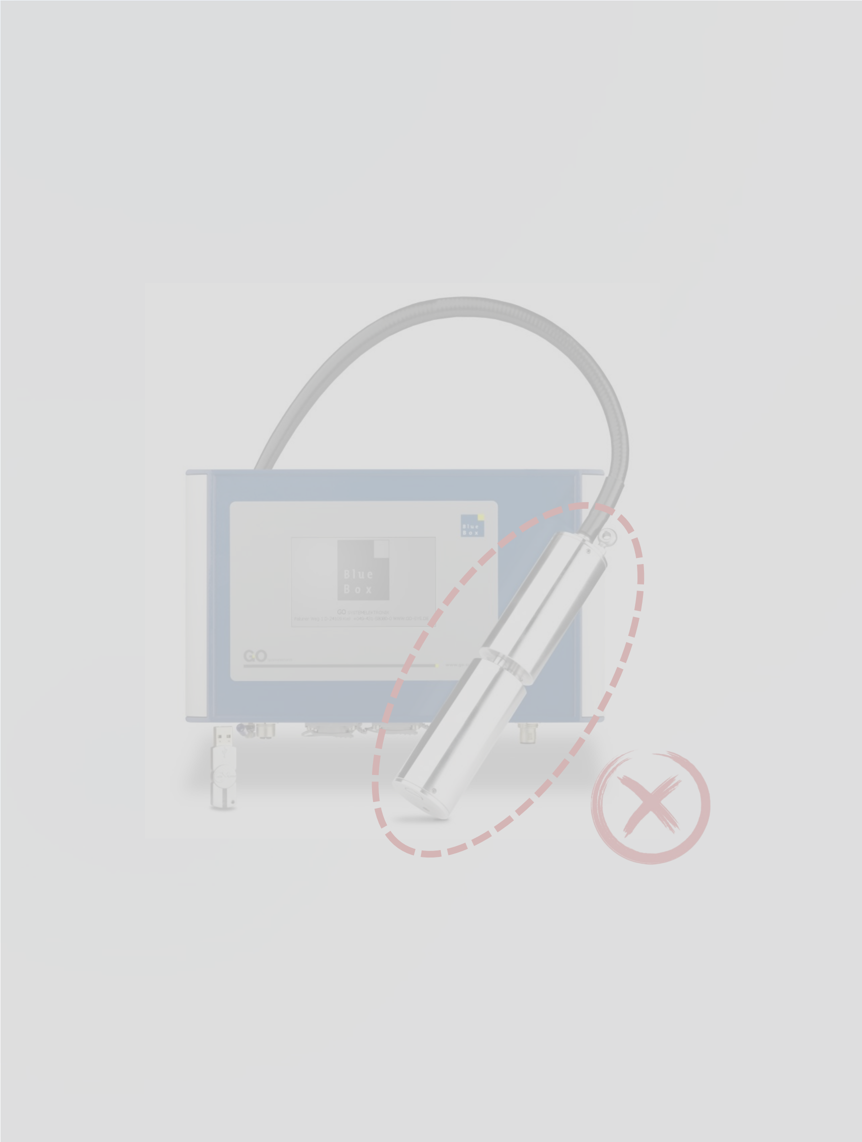
Physical model

NEED!!

Specific container
with prior knowledge

Unknown container

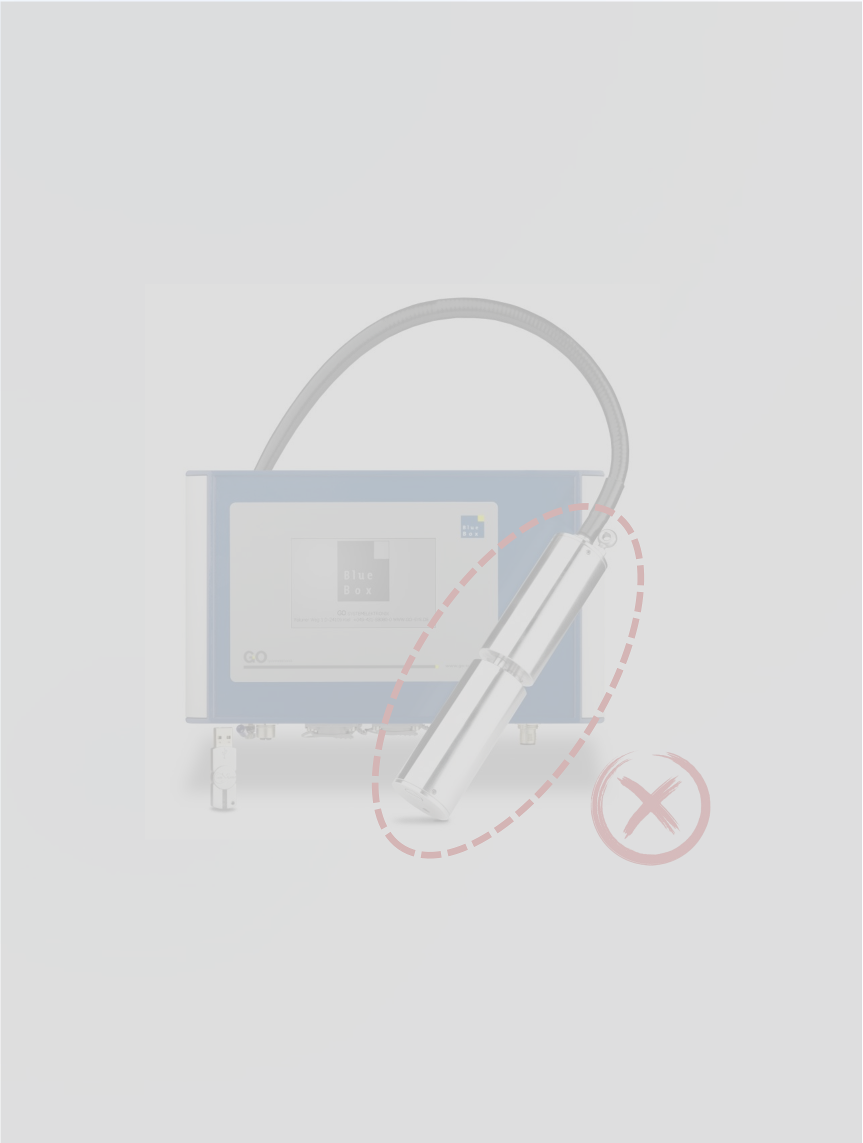
Motivation



Furthermore, liquid height is not free

Motivation

Therefore, Contact-based perception application scenarios are limited



specific container

Motivation

The existing fine-grained liquid recognition system is hard to be non-invasive

contact detection

specific container

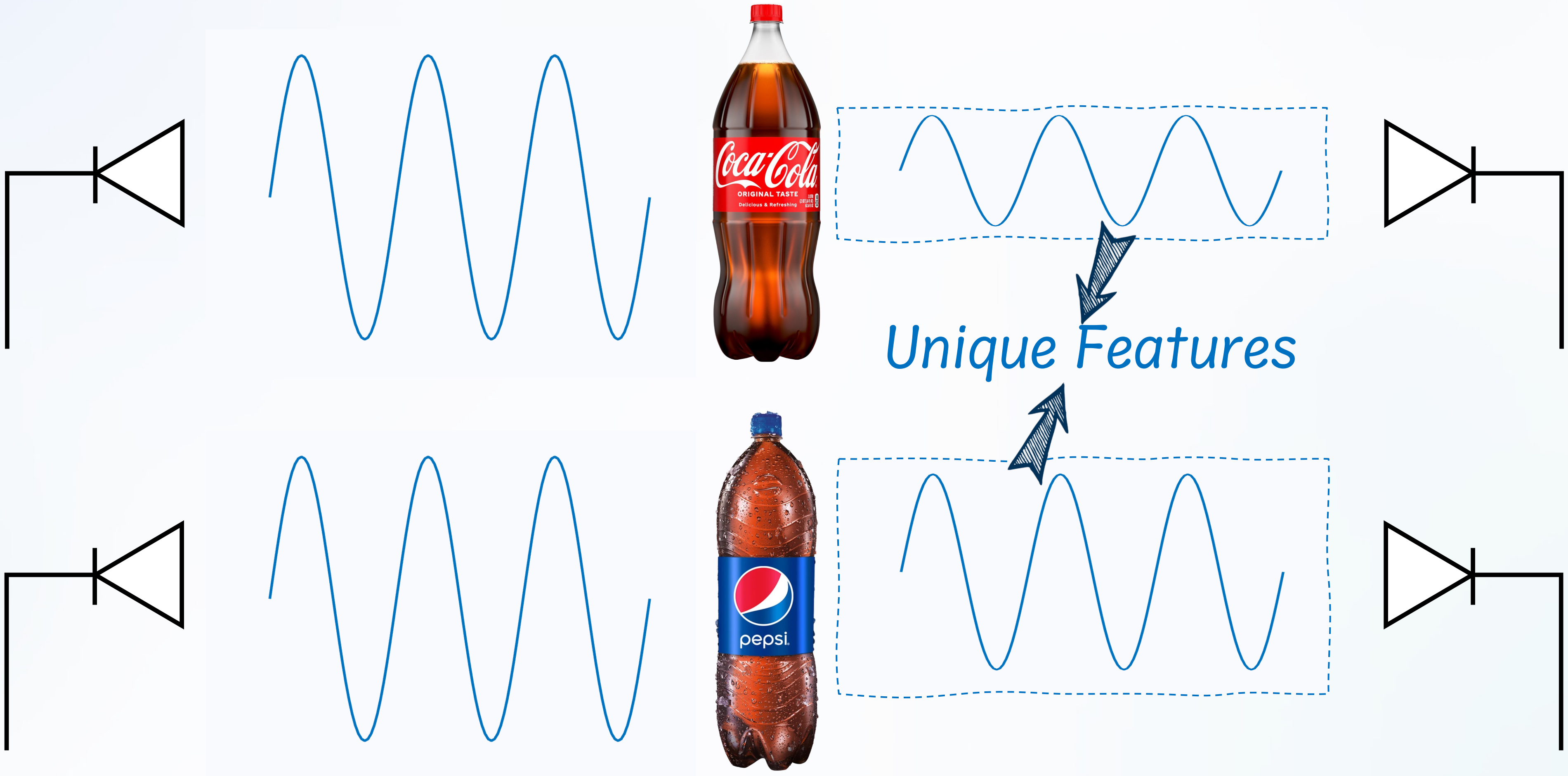
Could we design a *non-invasive* and *fine-grained* liquid recognition system?

Goals

- ✓ **Non-invasive:** be independent of the container's material and width, and the liquid's height.
- ✓ **Find-grained:** distinguish similar liquids such as alcohol solutions with a concentration difference of 1%.

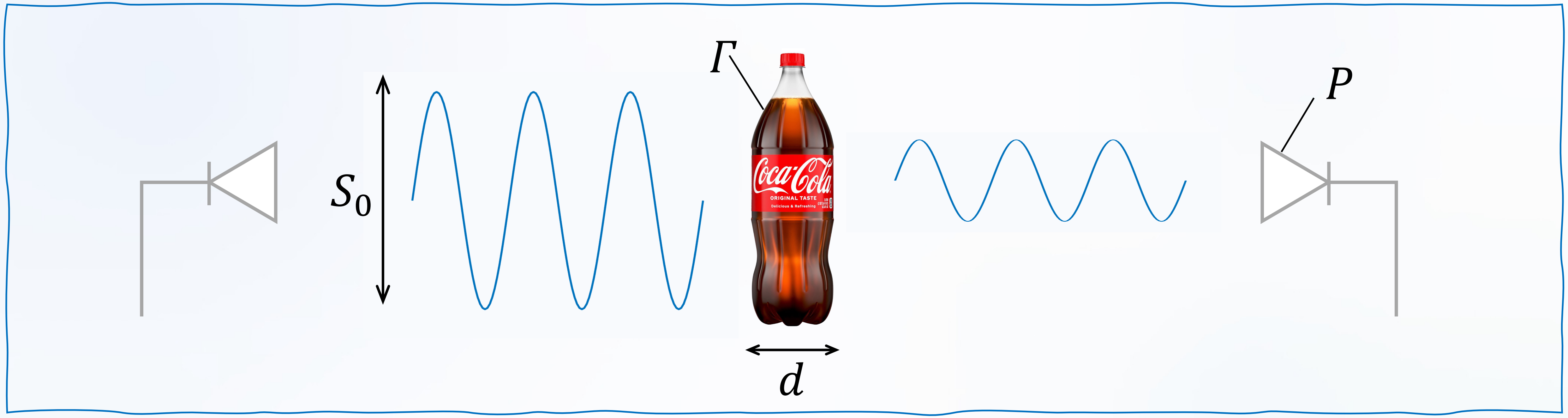
Inspiration

The attenuation of electromagnetic waves in different liquids are different



[1] Richard P Feynman, Robert B Leighton, and Matthew Sands. 2011. The Feynman lectures on physics, Vol. I: The new millennium edition: mainly mechanics, radiation, and heat. Vol. 1. Basic books

Basic Model



The strength of the received signal is given by:

$$S_r = \alpha(D_{air})\Gamma e^{-\beta d} P S_0$$

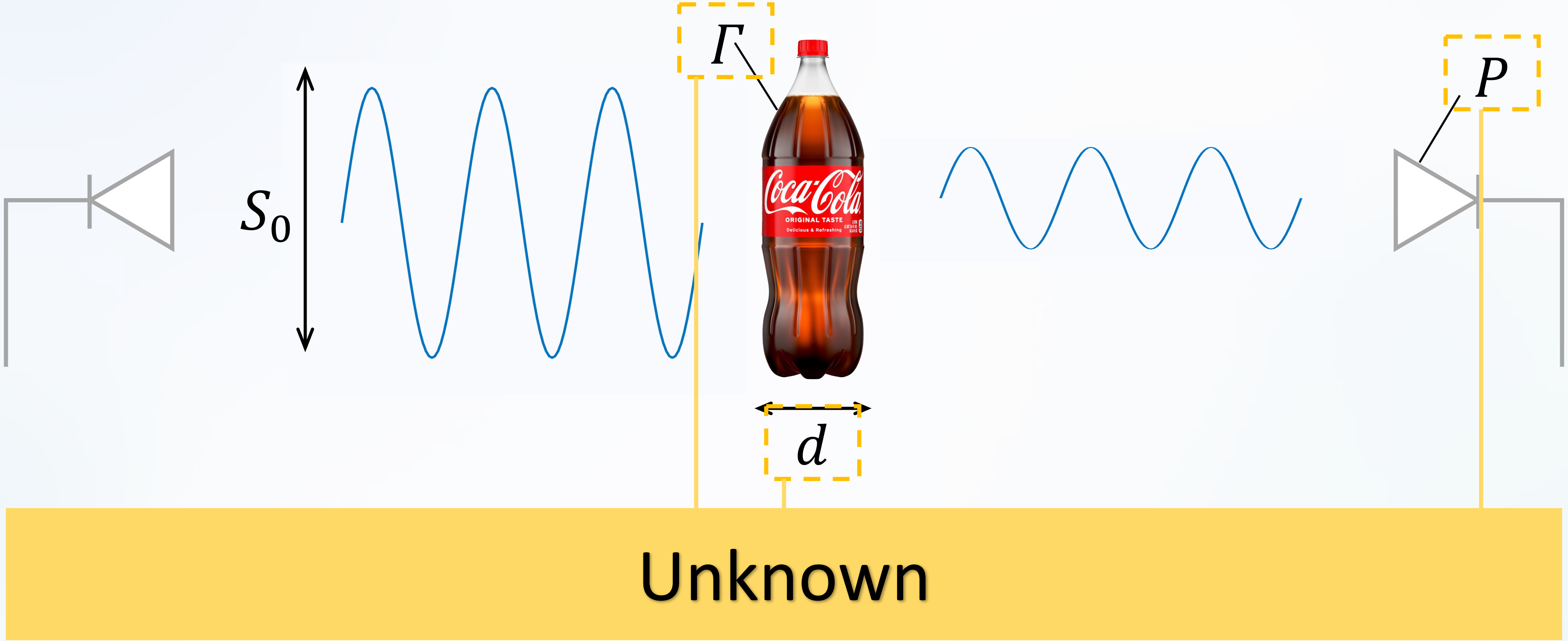
The attenuation of the waves are depended on β, which is the unique feature of the liquid

$\alpha(D_{air})$: *the attenuation in the air* Γ: *transmission coefficient of waves at dielectric interfaces*
d: *the signal transmission path in liquid* P: *gain of the receiving antenna*

[1] Ashutosh. A, etc, 2018. Liquid: A wireless liquid identifier. [2] Shan. J, etc, 2011. Electromagnetic wave propagation into fresh water.

Challenge

- *Equation is underdetermined* ⟹ *β are difficult to extract*



$$S_r = \alpha(D_{air})\Gamma e^{-\beta d} P S_0 \nRightarrow \beta$$

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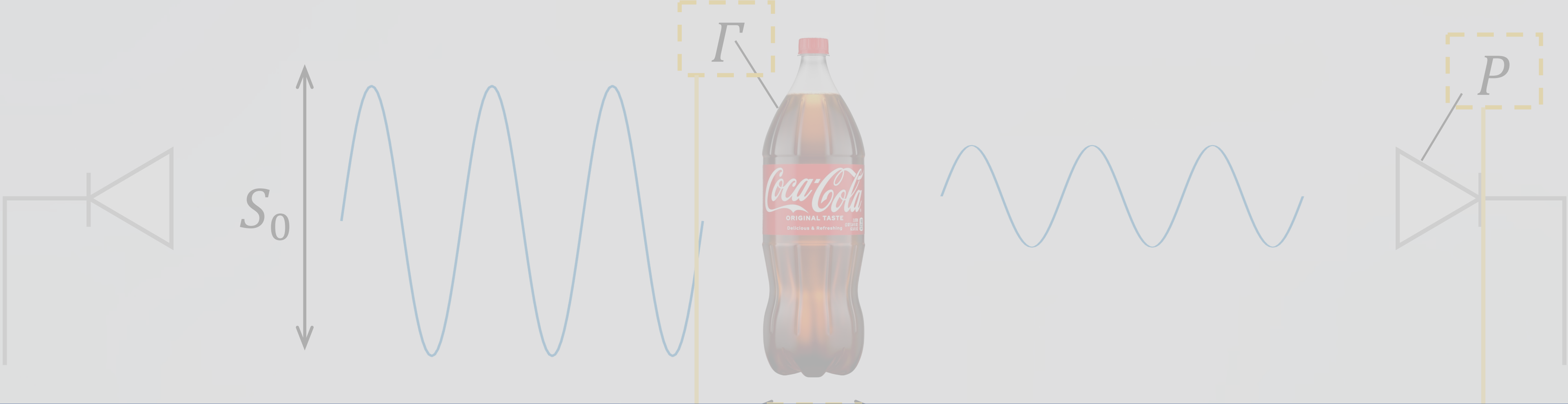
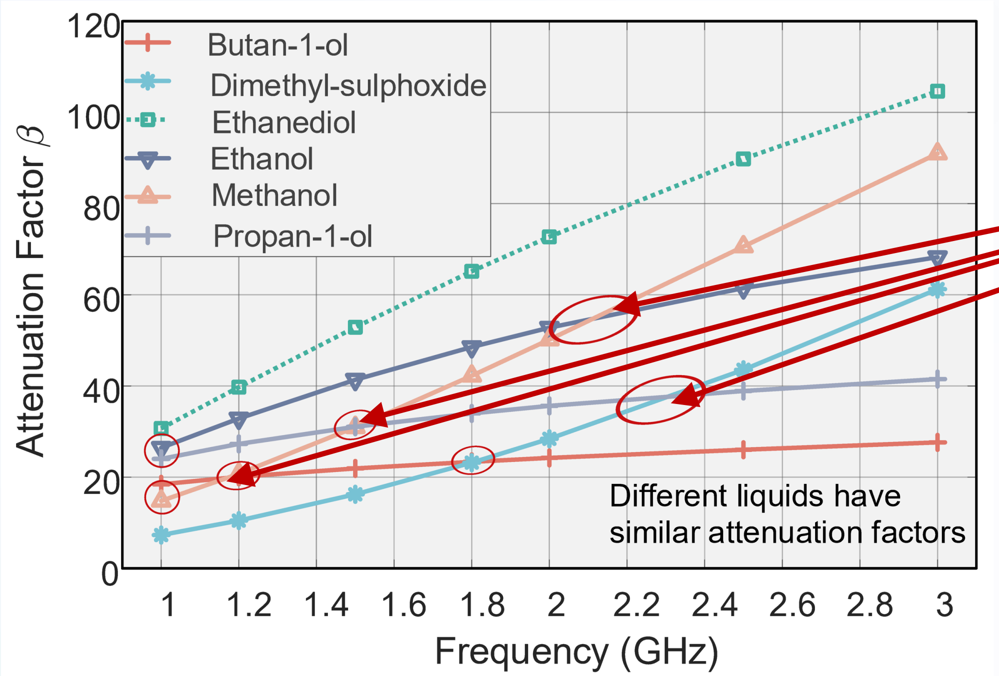


Q1: How to remove the effect of container (Γ and d) and antenna (P)?

$S_r = \alpha(D_{air})\Gamma e^{-\beta d} P S_0$ ⟹ β

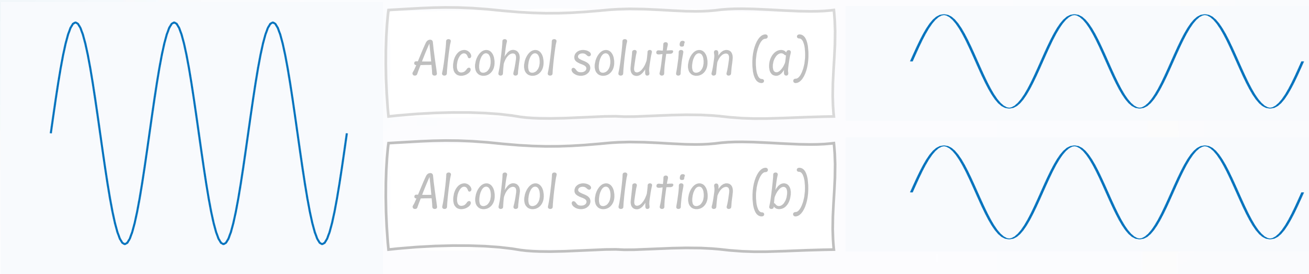
Challenge

- The differences between similar liquids are small



The attenuation factors are so similar

Indistinguishable

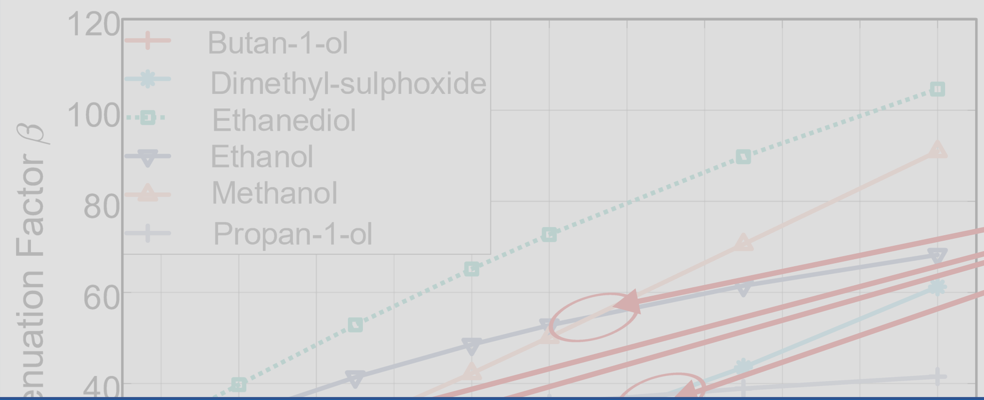


diff < 3% *

* The results are calculated using the data in the paper "Dielectric characterization of alcoholic beverages and solutions of ethanol in water under microwave radiation in the 1--20 GHz range"

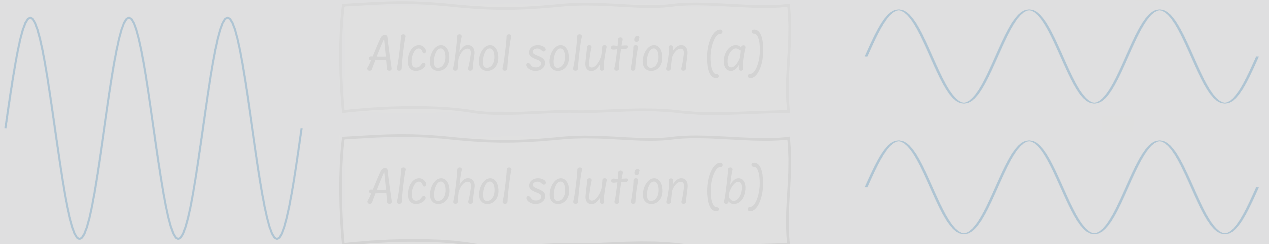
Challenge

- *The differences between similar liquids are small*



The attenuation factors are so similar

Q2: How to recognize liquids in a fine-grained level?



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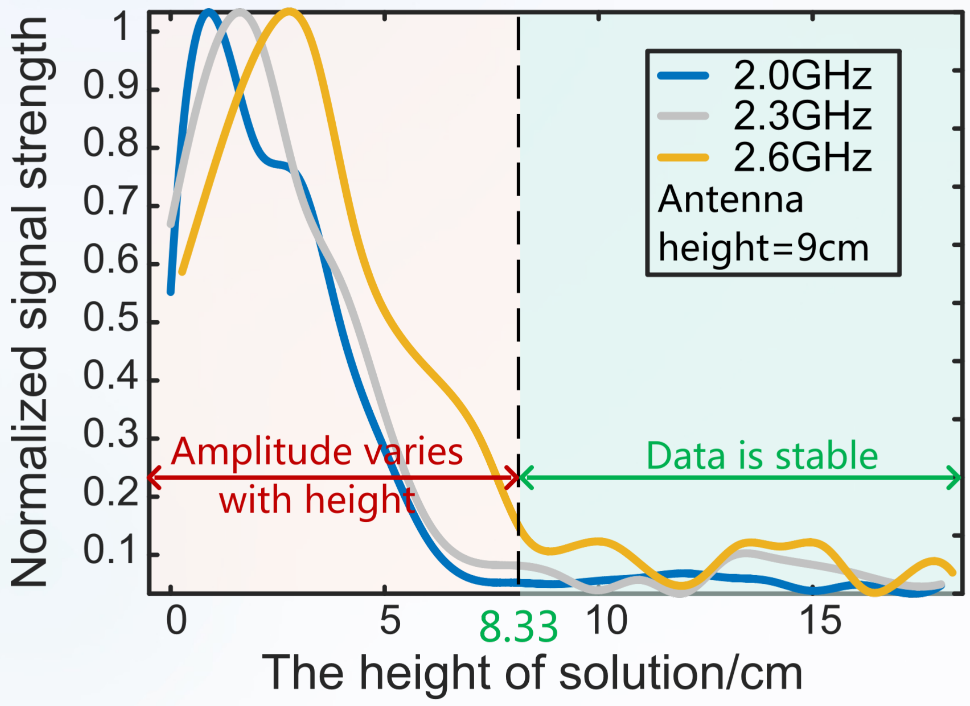
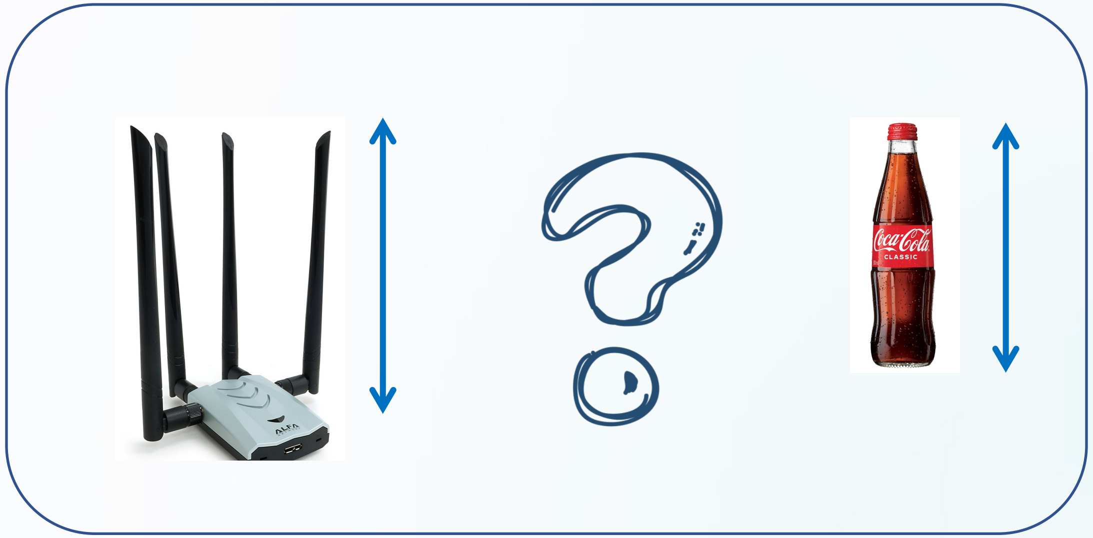
Challenge

- *Liquid height unknown* → *signal strength difficult to calibrate*



The signal strength is related to the height

However



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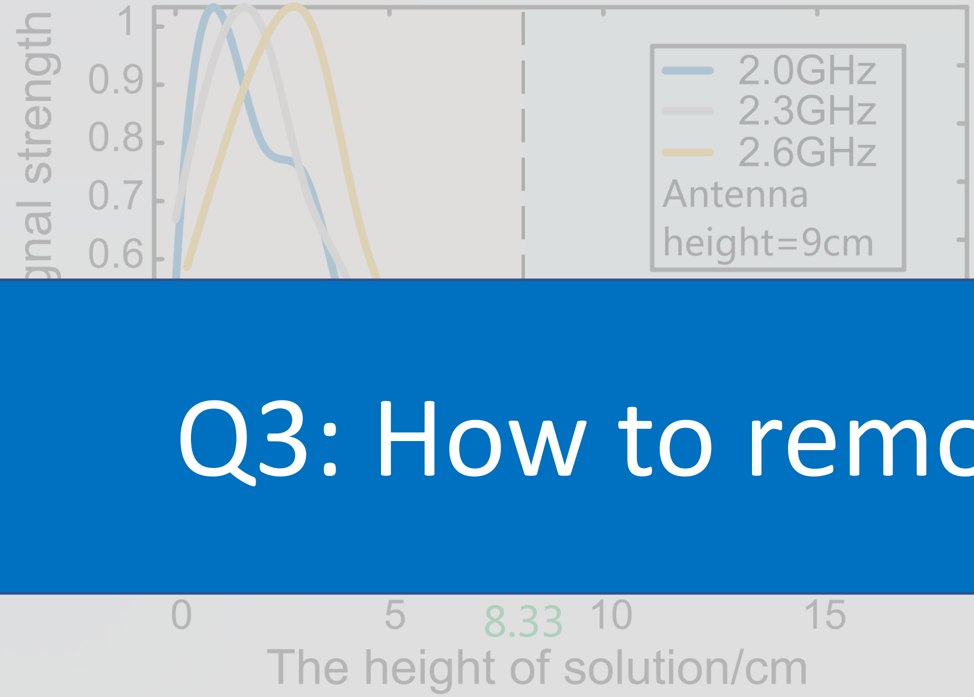

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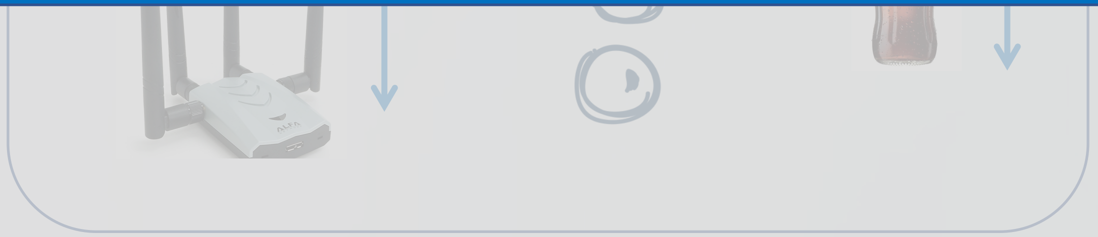
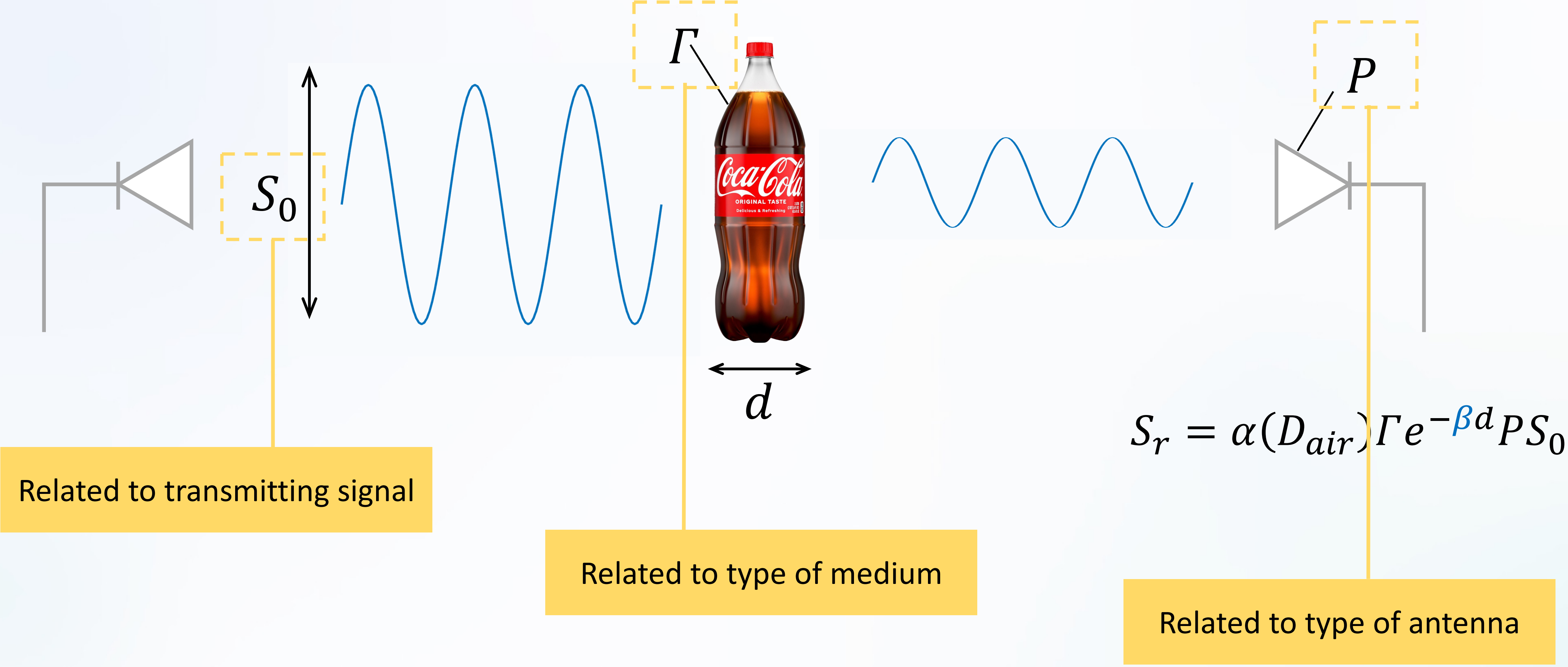


Q3: How to remove the effect of height?

Our solutions

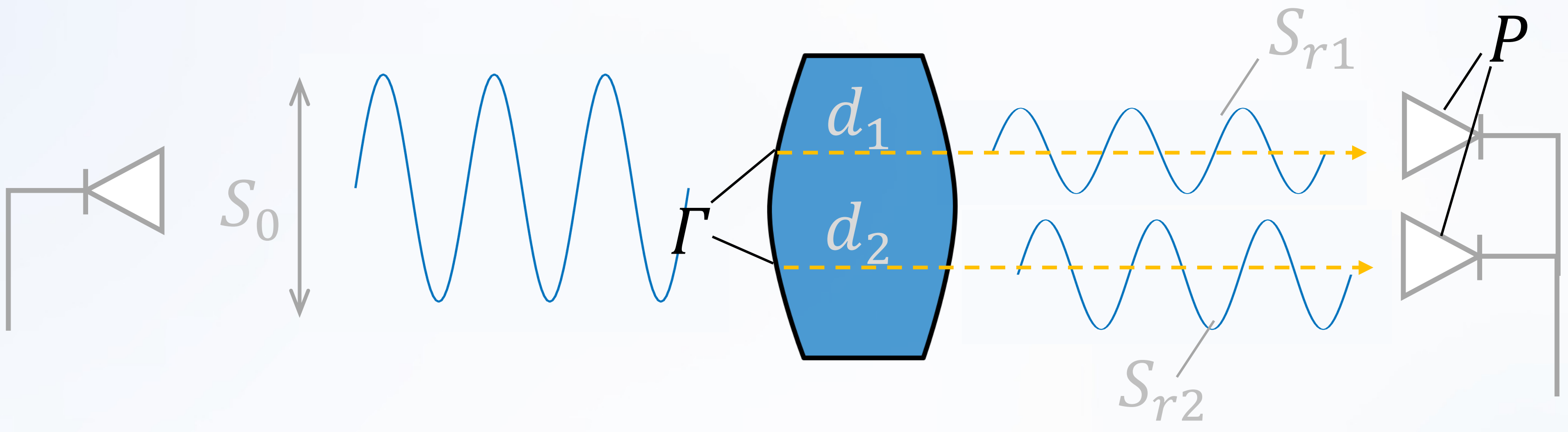
Q1: How to remove the effect of container and antenna?



$$S_r = \alpha(D_{air})\Gamma e^{-\beta d} P S_0$$

They are similar for multiple RF links

Q1: How to remove the effect of container and antenna?



We build a ***dual antenna model*** *to remove the influence*

$$S_{r1} = \alpha(D_{air})\Gamma e^{-\beta d_1} P S_0$$

$$S_{r2} = \alpha(D_{air})\Gamma e^{-\beta d_2} P S_0$$

$$\frac{S_{r1}}{S_{r2}} = e^{-\beta(d_1 - d_2)} = e^{-\beta \Delta d}$$

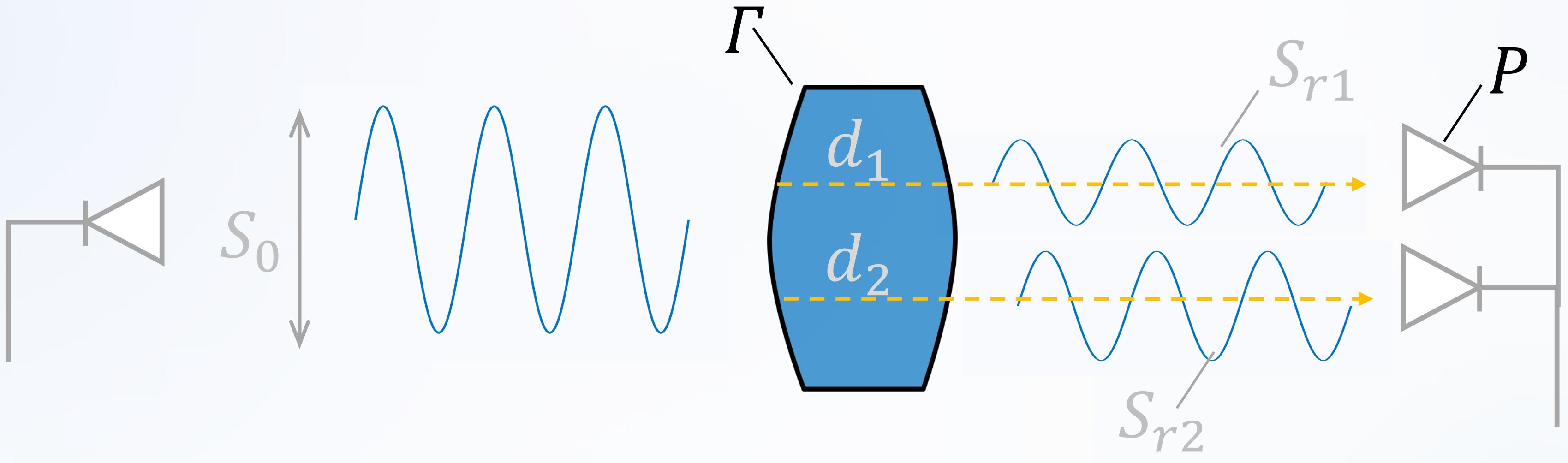
$\alpha(D_{air})$: the attenuation in the air

d: the signal transmission path in liquid

Γ: transmission coefficient of waves at dielectric interfaces

P: gain of the receiving antenna

Q1: How to remove the effect of container and antenna?



However, adding RF links doesn't help to eliminate Δd

$$S_{r1} = \alpha(D_{air})\Gamma e^{-\beta d_1} P S_0$$

$$S_{r2} = \alpha(D_{air})\Gamma e^{-\beta d_2} P S_0$$

$$\frac{S_{r1}}{S_{r2}} = e^{-\beta(d_1 - d_2)} = e^{-\beta \Delta d}$$

$\alpha(D_{air})$: the attenuation in the air

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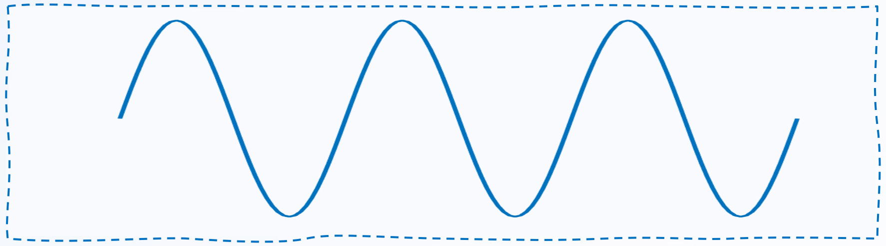
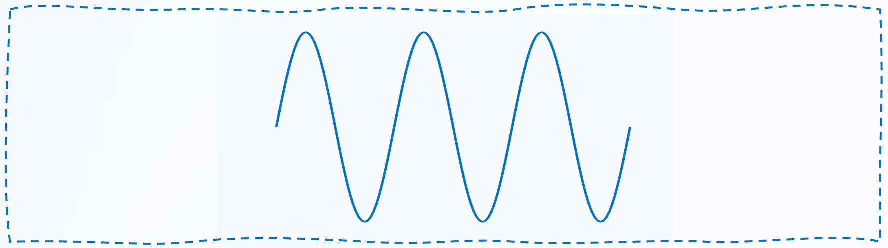
Q1: How to remove the effect of container and antenna?

The opportunity comes from that the attenuation factor β varies with frequency



$$\Delta S_r^{f_1} = e^{-\beta_1 \Delta d}$$

Frequency is f_1

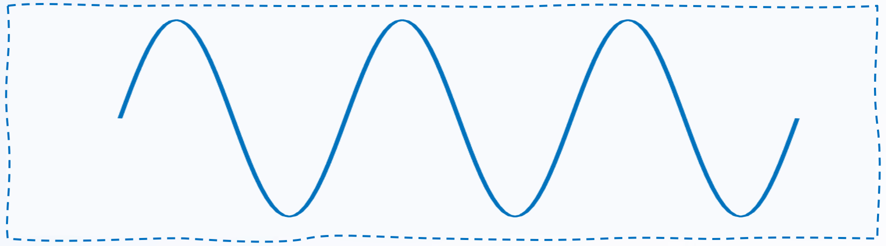


$$\Delta S_r^{f_2} = e^{-\beta_2 \Delta d}$$

Frequency is f_2

Q1: How to remove the effect of container and antenna?

The opportunity comes from that the attenuation factor β varies with frequency

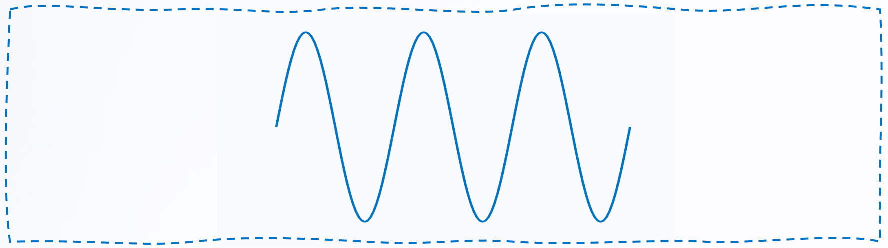


Frequency is f_1

$$\Delta S_r^{f_1} = e^{-\beta_1 \Delta d}$$

But Δd is *same*

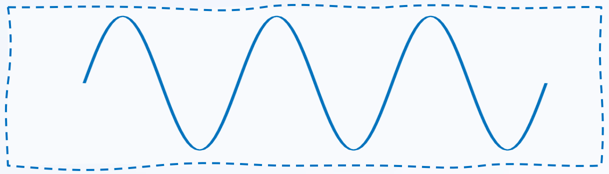
$$\Delta S_r^{f_2} = e^{-\beta_2 \Delta d}$$



Frequency is f_2

Q1: How to remove the effect of container and antenna?

We extract the relative frequency response factor as liquid feature, which is independent of the container width



Frequency is f_1

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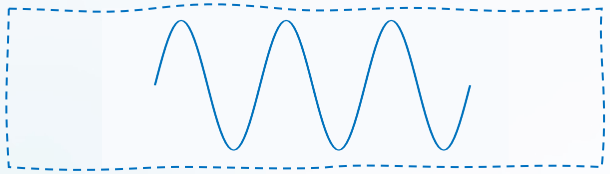


Frequency is f_2

$$\Delta S_r^{f_2} = e^{-\beta_2 \Delta d}$$

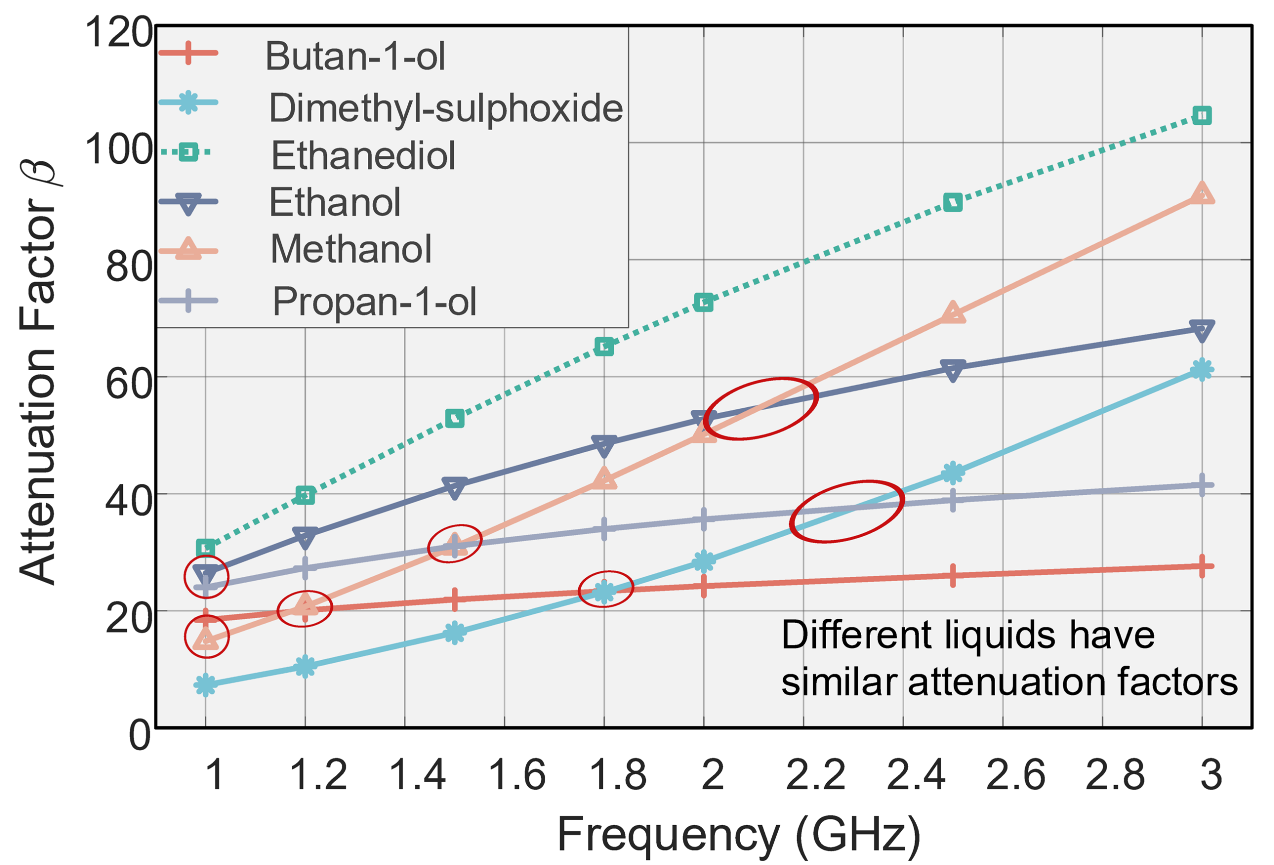
$$L_{2,1} = \frac{\ln\left(\Delta S_r^{f_1}\right)}{\ln\left(\Delta S_r^{f_2}\right)} = \beta_2 - \beta_1$$

With n frequencies, the relative frequency response factor is given by $F = [L_{n,n-1},\ L_{n,n-2}, \dots, L_{2,1}]$

f_i: the frequency of the wave
β_i: the attenuation factor when the frequency is f_i
Δd: the difference in the transmission distance of two signal in the liquid

Q2: How to recognize liquids in a fine-grained level?

The reason that liquids are different to distinguish is that the attenuation factors of them are similar



* The results are calculated using the data in the paper "Tables of the complex permittivity of dielectric reference liquids at frequencies up to 5 GHz."

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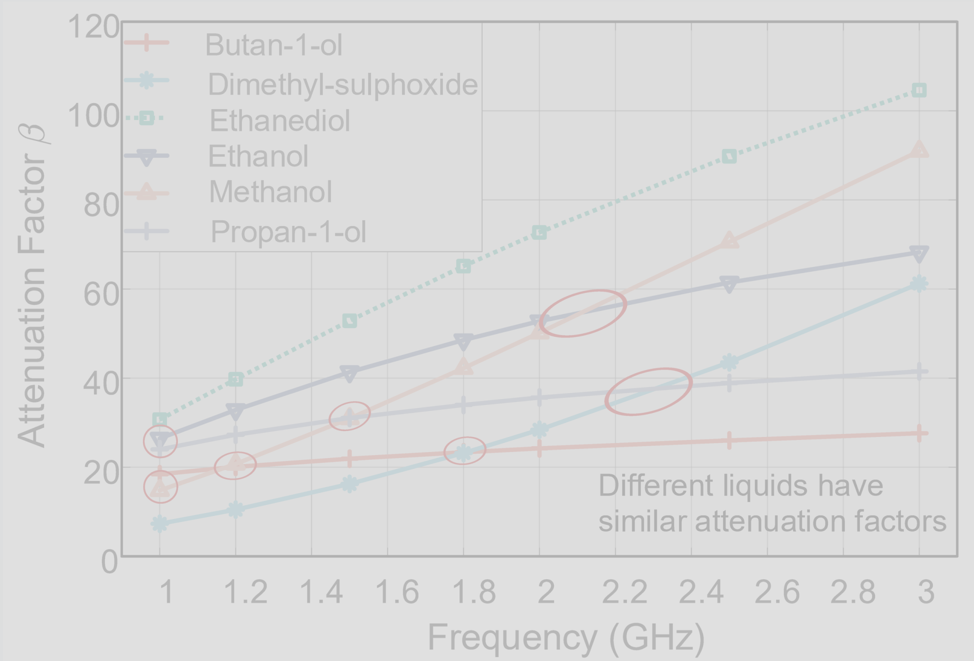
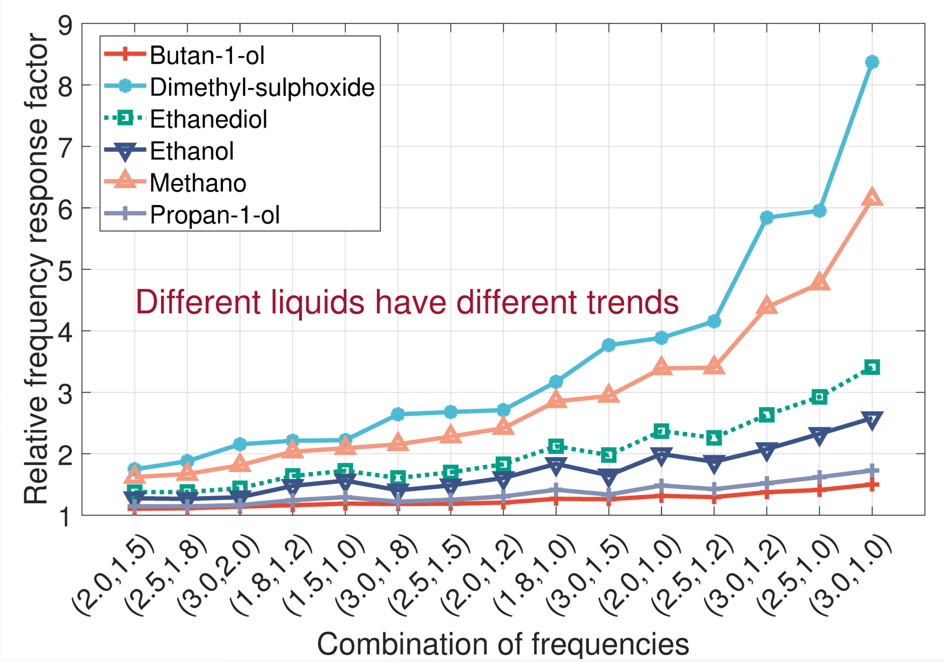


Compared with the attenuation factor, the relative frequency response factor has stronger discrimination ability



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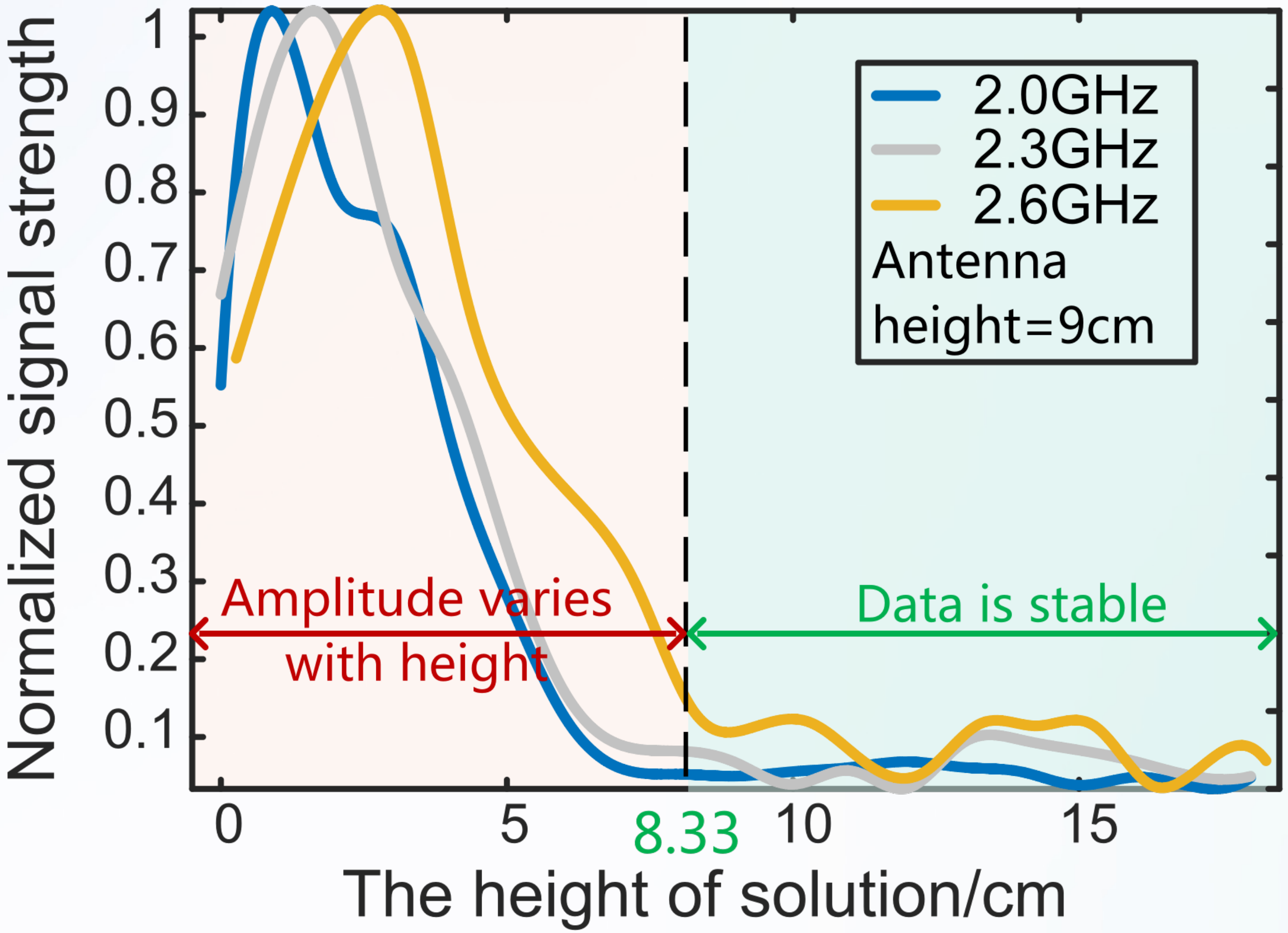
Q3: How to remove the effect of height?

When the liquid is lower than the antenna, the signal strength varies with the height



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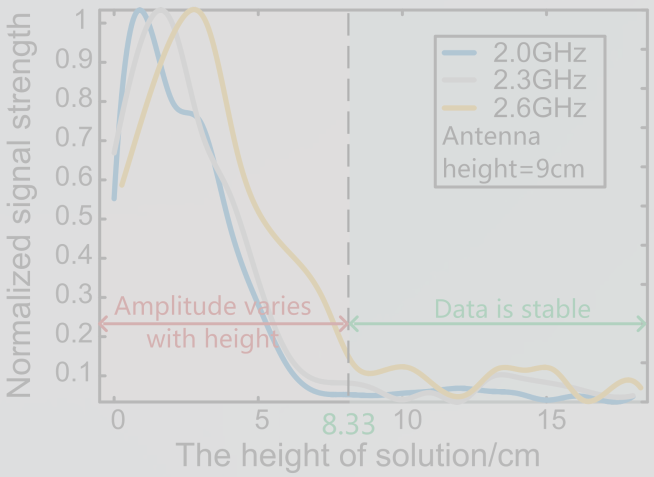
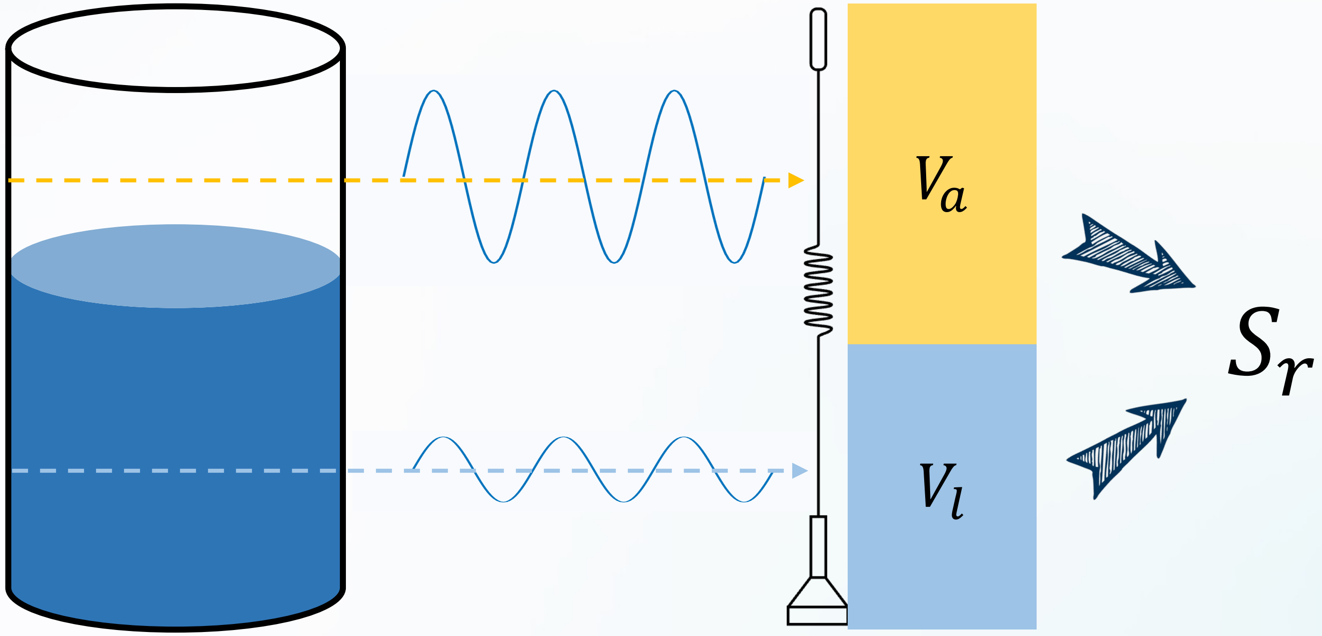


When the liquid is lower than the antenna, the signal strength varies with the height

The reason is that signal decays faster in liquid



The induced voltages excited by electromagnetic waves propagating in air and liquid are v_a and v_l, respectively

Q3: How to remove the effect of height?

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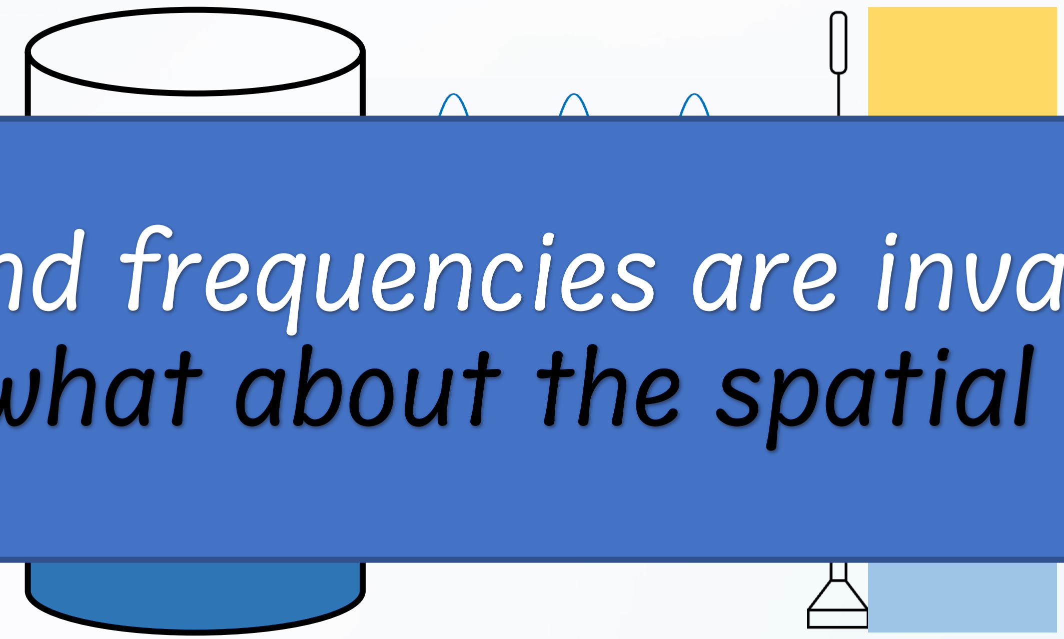


The induced voltages excited by electromagnetic waves propagating in air and liquid are v_a and v_l, respectively

Both adding RF links and frequencies are invalid

what about the spatial domain?

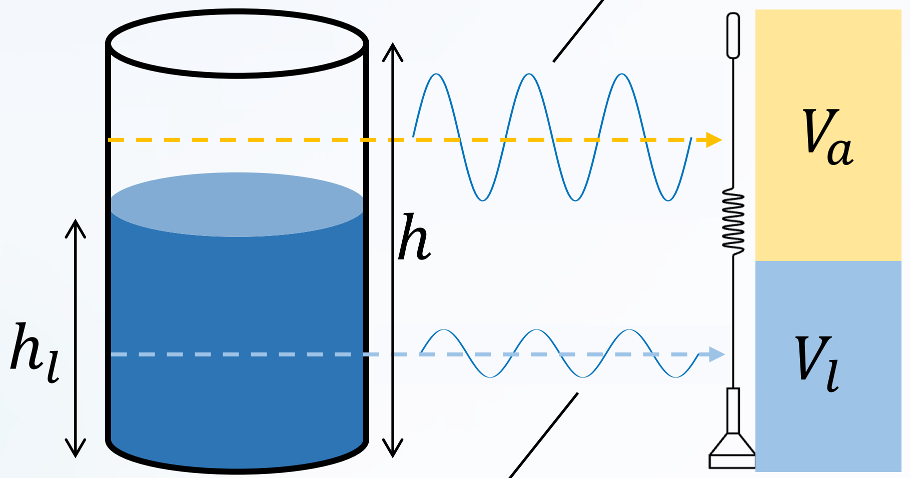
Q3: How to remove the effect of height?

only related to liquids

Q3: How to remove the effect of height?

We build a model of the electric field distribution in space and obtain the function relationship between the signal strength and the liquid height

$$E_a = \Gamma_a \alpha_a E_0$$



$$E_l = \Gamma_l \alpha_l e^{-\beta d} E_0 = \gamma e^{-\beta d} E_0$$

$$S_r^0 = \int_0^{h_l} E_l f(y)dy + \int_{h_l}^{h} E_a f(y)dy$$

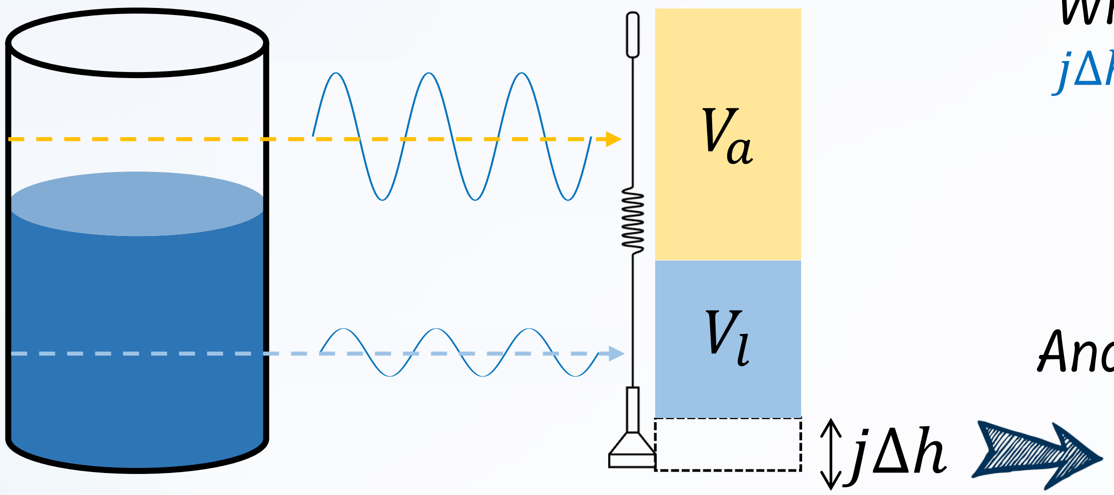
$$= \gamma e^{-\beta d} E_a \int_0^{h_l} f(y)dy + E_a \int_{h_l}^{h} f(y)dy$$

α: the attenuation in the air　　Γ: transmission coefficient at dielectric interfaces　　d: the signal transmission path in liquid

β: the attenuation factor　　h: the height of the received antenna　　h_l: the height of the liquid

Q3: How to remove the effect of height?

Difference method is utilized!



When the transmitting antenna is at position $j\Delta h$, the received signal strength is given by:

$$S_r^j = \gamma e^{-\beta d} E_a \int_{j\Delta h}^{h_l} f(y)dy + E_a \int_{h_l}^{h} f(y)dy$$

And we denote

$$\Delta a = S_r^{j+1} - S_r^j = \gamma e^{-\beta d} E_a f(j\Delta h)\Delta h$$

α: the attenuation in the air Γ: transmission coefficient at dielectric interfaces d: the signal transmission path in liquid
β: the attenuation factor h: the height of the received antenna h_l: the height of the liquid

Q3: How to remove the effect of height?

And we denote

$$\Delta a = S_r^{j+1} - S_r^j$$
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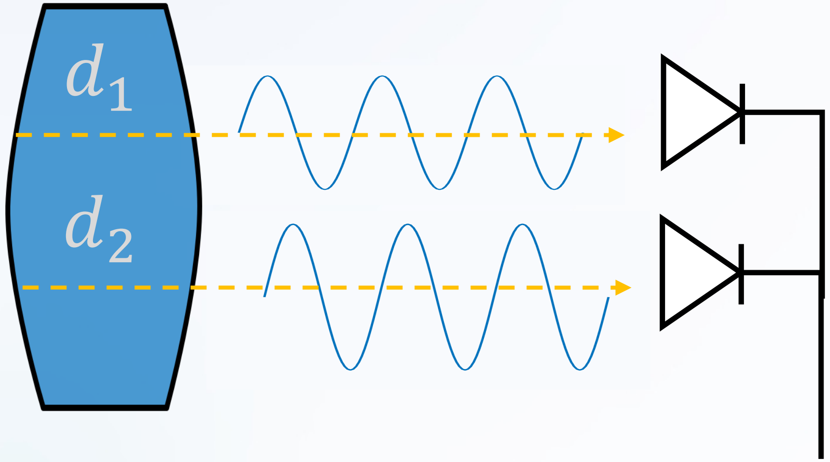

When we consider the ratio of the two antennas

$$\frac{\gamma e^{-\beta d_1} E_a f(j\Delta h)\Delta h}{\gamma e^{-\beta d_2} E_a f(j\Delta h)\Delta h} = e^{-\beta \Delta \mathrm{d}}$$

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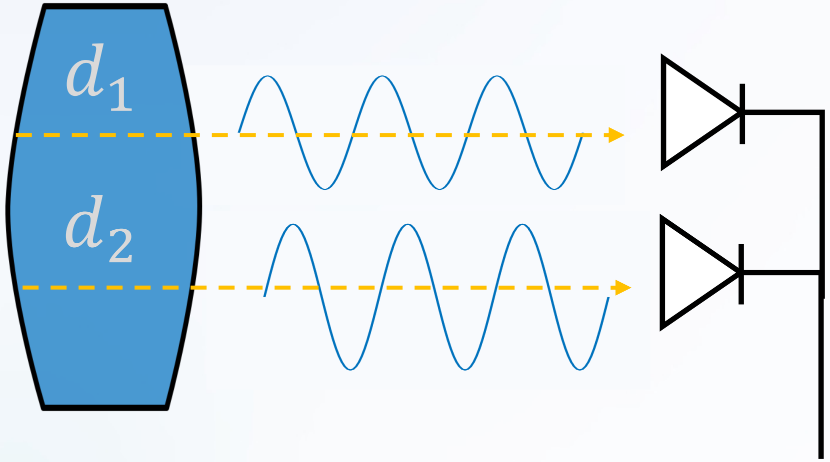

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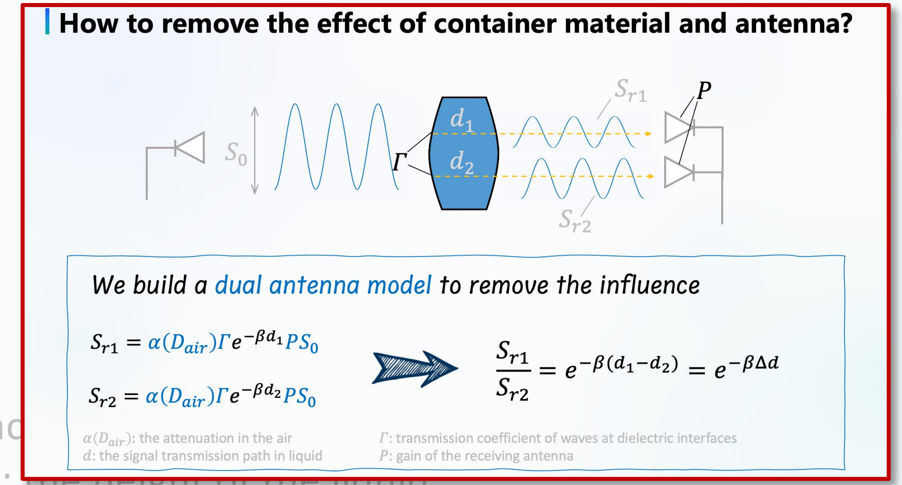
Same to



α: the attenuation in the air Γ: transmission coefficient at dielectric interfac

β: the attenuation factor h: the height of the received antenna h_l: the height of the liquid

Practical issues

- *How many frequencies are required?*
- *Does the diffraction affect liquid identification?*

Practical issues - select the frequencies

Frequency (GHz)	Accuracy rate of concentration recognition	Accuracy rate of species recognition
1.7	65.53%	73.33%
2.0	73.74%	77.93%
2.4	55.38%	63.64%
2.6	70.49%	74.07%
5.0	74.66%	77.12%
1.7,2.0,2.4	83.62%	88.77%
1.7,2.6,5.0	88.71%	90.19%
1.7,2.0, 2.4, 2.6	94.92%	97.30%
1.7,2.0, 2.4, 2.6, 5.0	95.72%	98.93%

Accuracy

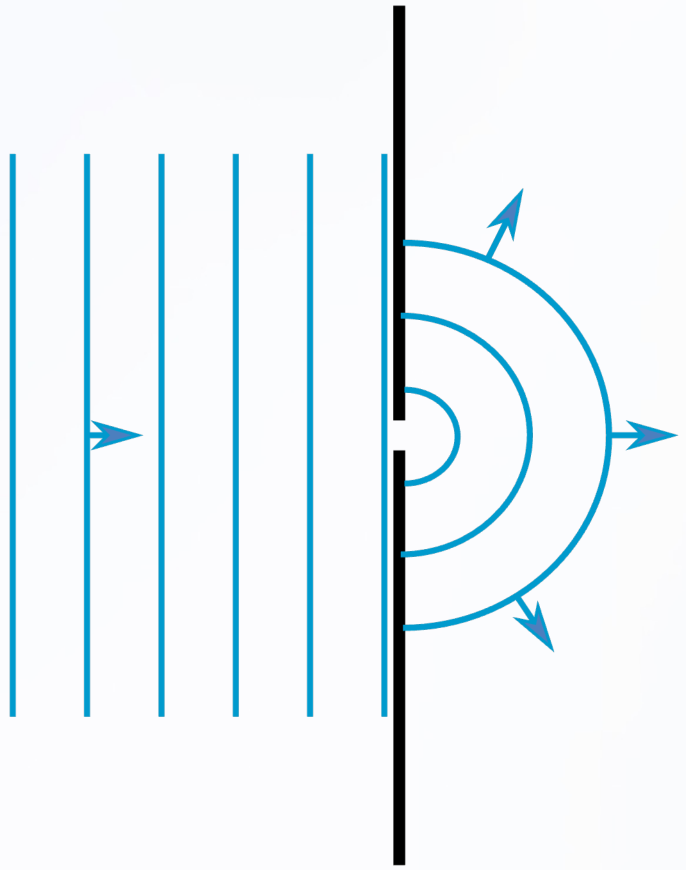
Band resources

Data scale

Be selected

Practical issues-Diffraction

When the size of the obstacle is similar to the wavelength, the wave will deviate from the original direction of propagation



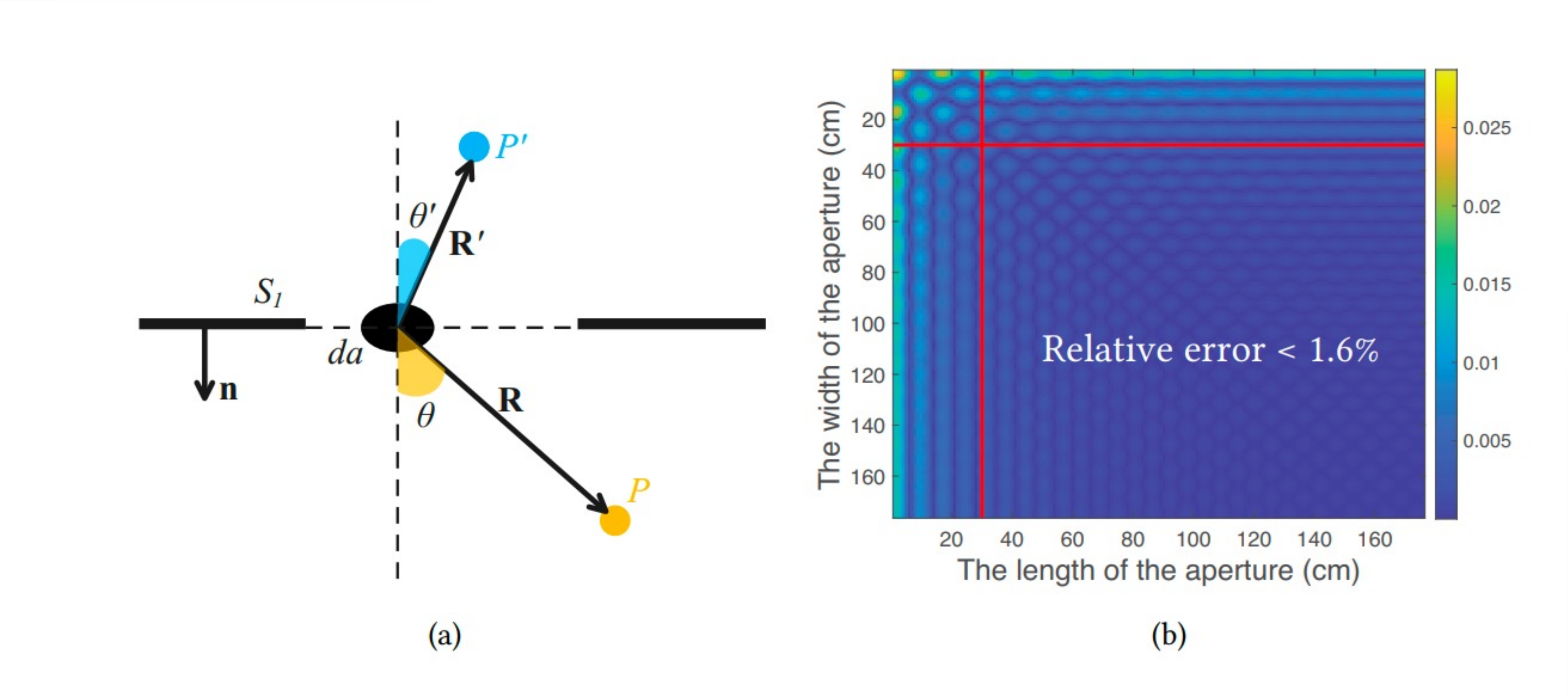
Practical issues-Diffraction

When the size of the obstacle is similar to the wavelength, the wave will deviate from the original direction of propagation

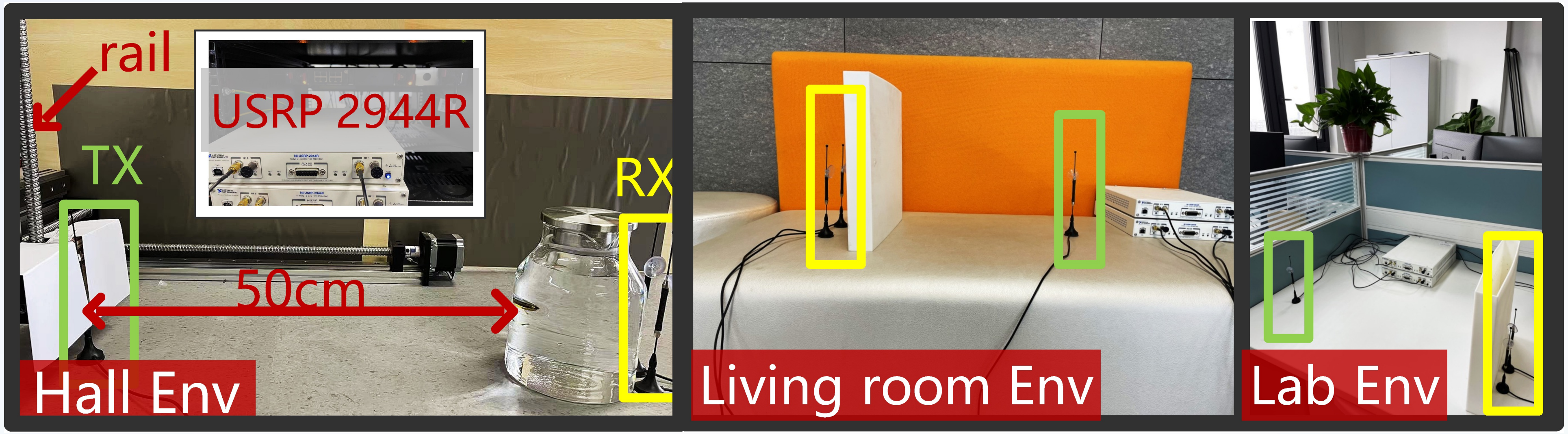
Does diffraction affect Liqray's liquid identification?

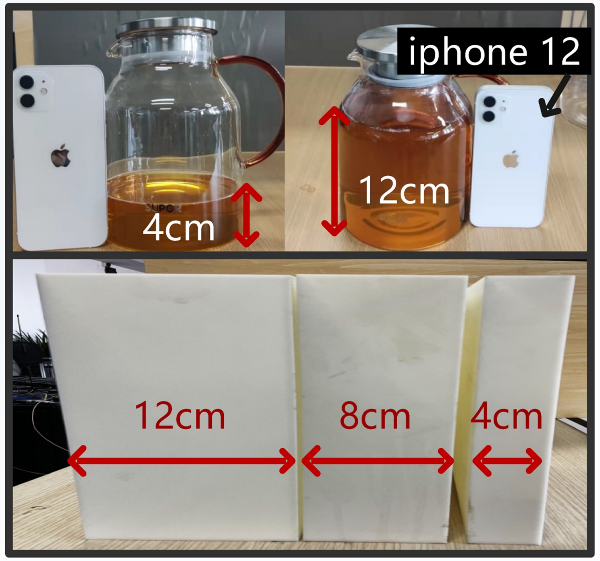
Practical issues-Diffraction

When the length of the container is greater than 30cm, the error caused by diffraction is less than 1.6%



Evaluation

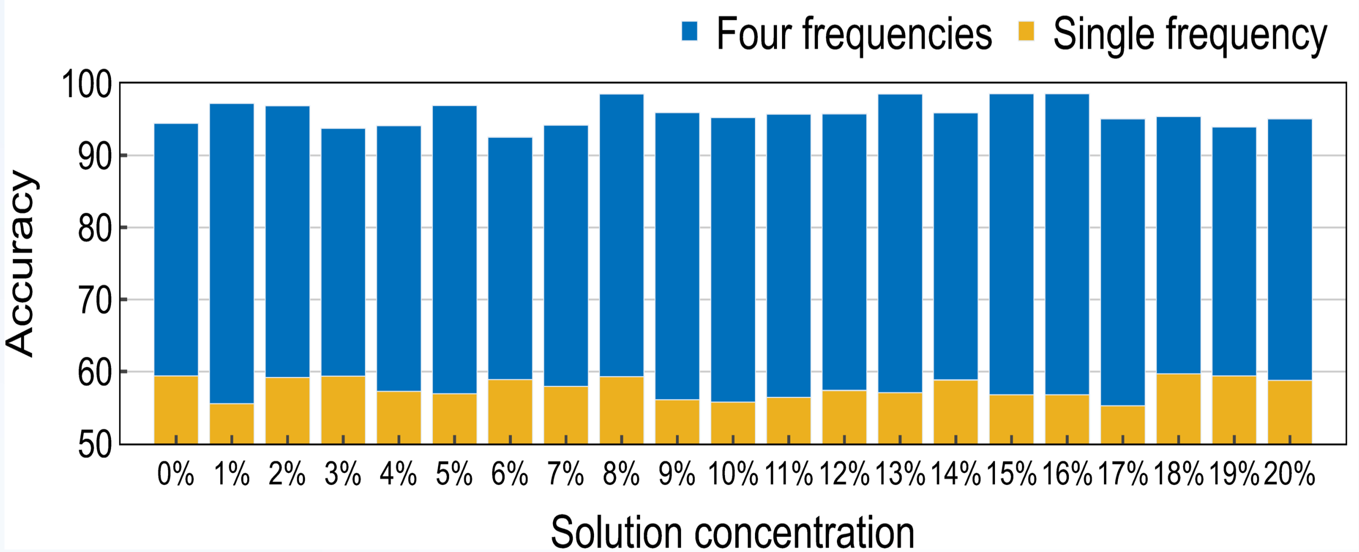




Experimental setup

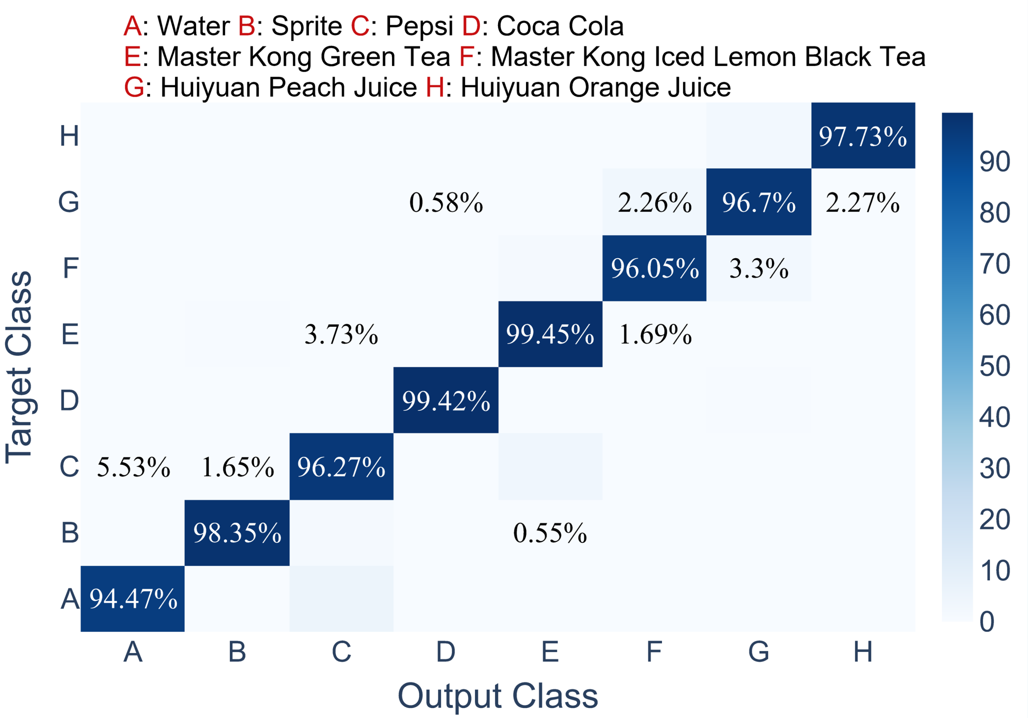
- *N2944R USRP devices*
- *A transmitting and two receiving antennas*
- *Resin container with different width*

Evaluation- Identification

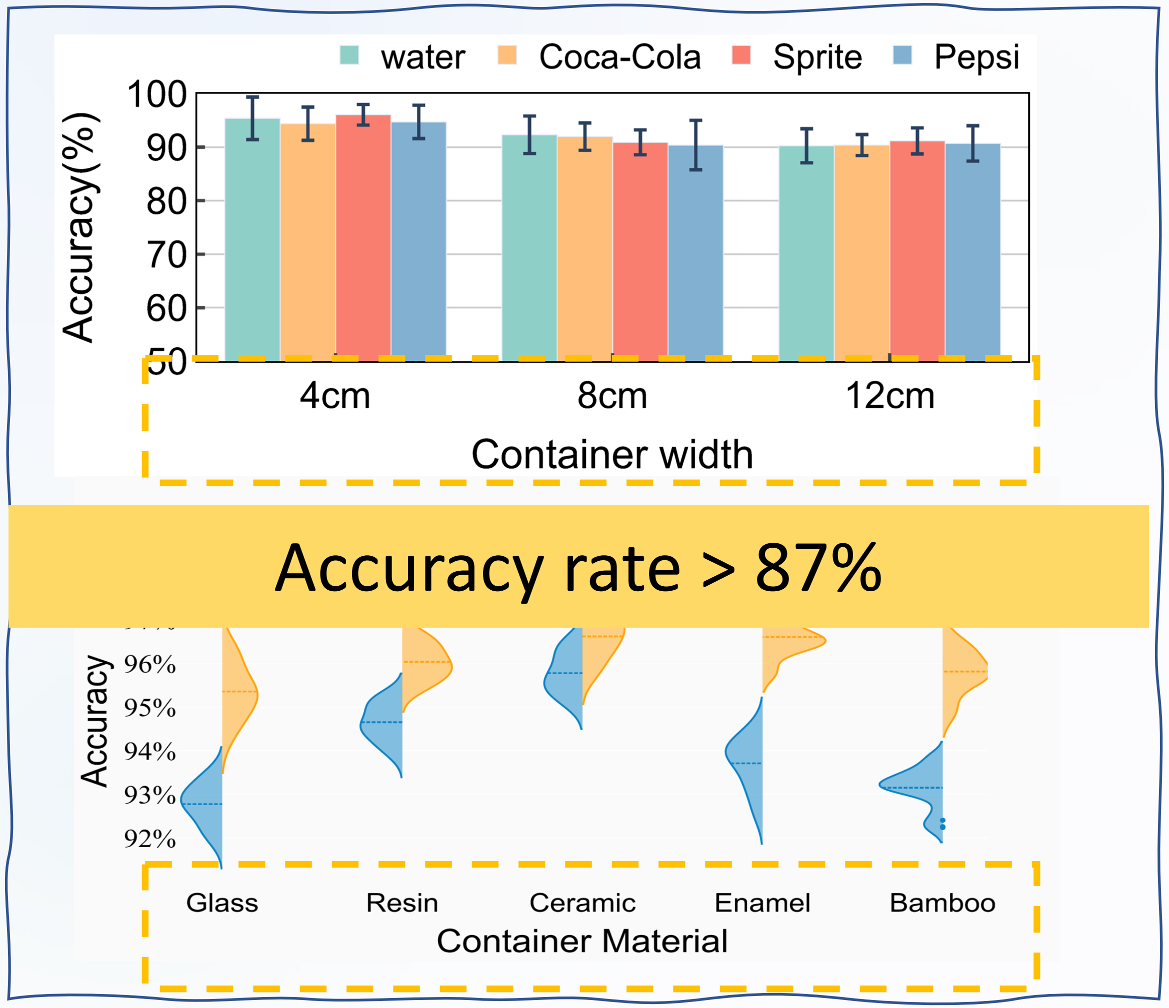


The accuracy of concentration identification is more than 90%

The average accuracy of liquid identification is 95%



Evaluation- Container and Height



Accuracy rate > 87%

Error < 7%

Limitations and Future work

Oil-based liquids

Metal container

Conclusion

- *This paper presents LiqRay, a non-invasive and fine-grained system that can use RF signals to recognize liquids.*
- *It can cope with different containers and solution heights.*
- *Our model-driven scheme is making efforts to cultivate liquid recognition system pervasive for more applications and scenarios.*

Thank You!